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The ACTS Mobile Terminal

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Throughout the 1980s, NASA, through JPL, has been involved in the development and demonstration of system concepts and high-risk technologies to enable the introduction of commercial mobile satellite services at L-band. The final phase of this effort, technology transfer to U.S. industry, is now well under way.

At present, a host of U.S. and international companies are competing to develop and place into service a variety of L-band commercial mobile satellite systems. In view of the inevitable congestion as a result of the limited bandwidth available at L-band, JPL has begun exploring alternative frequency bands to provide mobile and personal services to a larger user base. Due to the existing allocations at C-, X- and Ku-bands, JPL has focused its attention on Ka-band, which has outstanding potential because of the available bandwidth.

Essential for the success of any future telecommunication system is its ability to provide many users with a diversity of services in a cost-effective manner. A cornerstone to system viability is exploiting economies of scale to reduce user equipment cost. This leads to the requirement of a considerable system capacity to support a large pool of users and their varied demands. Bandwidth limitations form an eventual barrier at L-band. The use of Ka-band is intended to overcome this limitation. Moreover, Ka-band has the potential to support user equipment that is significantly smaller and potentially simpler than equipment using L-band. Ka-band is therefore a good candidate to achieve the large capacities, service diversity and convenience sought by users.

Ka-band, however, poses significant challenges, including a young technology with lossy RF components, significant rain attenuation, potentially large frequency uncertainties and large Doppler shifts in mobile applications. JPL's technology development goal has been to overcome these challenges with system architectures and components that attempt to exploit the potential benefits of migration to Ka-band — specifically reduction in size and complexity relative to L-band. Coupled with these gains, the large system capacities possible at Ka-band should lead to significant reductions in the cost of mobile satellite communications.

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The Satellite Communications (SATCOM) Program is managed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The goals of this Program are to develop advanced system concepts and technologies in the areas of mobile, micro and personal communications. A major thrust of the Program through the mid-1990s is the development of the mobile terminal to operate with NASA's Advanced Communications Technology Satellite.

Since Ka-band has the long-term potential to support a variety of user equipment concepts, JPL's approach has been to develop a Ka-band test-bed through which progressively more advanced technologies can evolve. From JPL's experience with MSAT-X, it has become evident that the presence of a space segment compatible with the technologies being developed is indispensable for their timely demonstration. NASA has been pursuing the use of Ka-band for stationary high-data-rate applications through the Advanced Communications Technology Satellite (ACTS).

ACTS possesses the high-gain spot-beam antennas required to support small mobile and personal user terminals. As such, the satellite provides an invaluable opportunity to demonstrate these technologies. ACTS is presently scheduled for launch in late 1992. Consistent with ACTS' availability and JPL's experience in mobile communications, the first development target will be a Ka-band mobile terminal. It has been named the ACTS Mobile Terminal (AMT), although it is intended to be a Ka-band technology test-bed that will support the long-term goals of micro and personal terminal development.

AMT Project

The AMT project was initiated in June 1990. To realize the potential of Ka-band in supporting mobile users, the following tasks are being performed or are scheduled. First, the challenges arising from mobile operation at Ka-band — namely, Doppler shifts, shadowing, satellite tracking with a high-gain antenna and rain attenuation — are being quantified, and system and subsystem solutions are being devised. Second, the mobile terminal is being designed and implemented with enabling technologies and channel compensation algorithms to meet the various requirements of Ka-band operation. Third, a set of experiments and demonstrations will be performed in 1993 and 1994 using ACTS. Both voice and data links (rate selectable according to channel conditions) will be demonstrated in typical mobile and stationary environments. Basic technologies that enable Ka-band communications will be demonstrated first, followed by various enhancements to improve system performance and efficiency. The demonstration vehicle will be equipped with state-of-the-art recording and analysis equipment to permit real-time and detailed post-experiment analysis of mobile channel operations.

These demonstrations will lead to the fourth phase of the AMT project — experiment analysis and engineering assessment. The data

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obtained from the experiments will be analyzed to improve the understanding of the Ka-band environment. The efficacy of the technologies and terminal design will be determined. The channel compensation schemes will be evaluated to assess the degree of terminal performance improvement against the ensuing terminal complexity. Finally, a series of recommendations for mobile service operation in this band will be published in a summary report.

Future AMT demonstration experiments are presently being explored. These include experiments to investigate the integration of satellite and terrestrial services (for example, call handover protocols), aeronautical and maritime equipment, and experiments to test alternate access or modulation schemes leading to the demonstration of a Ka-band personal/mobile satellite network. These activities will evolve from the AMT and will rely primarily on ACTS to provide the required space segment resources. Some activities will likely be performed in cooperation with industry.

AMT System Architecture and Operation

Studies focusing on Ka-band have explored system architectures and multiple access schemes that can form the basis for a viable mobile and personal satellite communication system [1–4]. These studies have shown that for continental U.S. (CONUS) coverage, a geosynchronous satellite would be most practical. The AMT system generally takes the form depicted in Figure 1. A fixed station (or hub, supplier or base station) communicates through the satellite with a large number of mobile or personal users scattered over CONUS. To alleviate the effective isotopic radiated power (EIRP) burden on the user terminal, satellite spot beams are used in covering CONUS.

In principle, the satellite could be of the bent-pipe or processing type. However, since the onboard processing system to support a large mobile user base is still in its infancy, this type of satellite can not be advocated without a complex trade-off study. Studies have also shown that a nonprocessing, geosynchronous satellite in the bent-pipe mode could be utilized effectively with a combination of multiple access schemes [1,3]. Combining frequency division multiple access (FDMA) or code division multiple access (CDMA) with time division multiple access (TDMA), capacities of 30,000 4.8-kbps channels have been predicted for a 6,000-lb-class satellite (GTO). The bandwidth required is roughly 300 MHz.

For the AMT, the geosynchronous bent-pipe satellite architecture has been retained. To be consistent with ACTS, uplinks will be at 30 GHz and downlinks at 20 GHz, as shown in Figure 1. To be compatible with a satellite experiment scheduled for early 1993, FDMA was selected for the base technology demonstration due to its lower risk. Technologies specific to CDMA and TDMA have been assigned to the follow-on enhancements.

In the FDMA architecture utilized, an unmodulated pilot is transmitted from the fixed station to each user spot beam. This pilot is used by the mobile terminal for antenna tracking, as a frequency reference for Doppler correction and precompensation, and for measuring rain attenuation. For system efficiency, a pilot is transmitted only in the forward direction, i.e., from the fixed to the mobile terminal. Hence, for the AMT, two signals will exist in the forward direction — the pilot and the information link — which could be voice or data. In the return direction (mobile to fixed), only the information channel (data channel) is

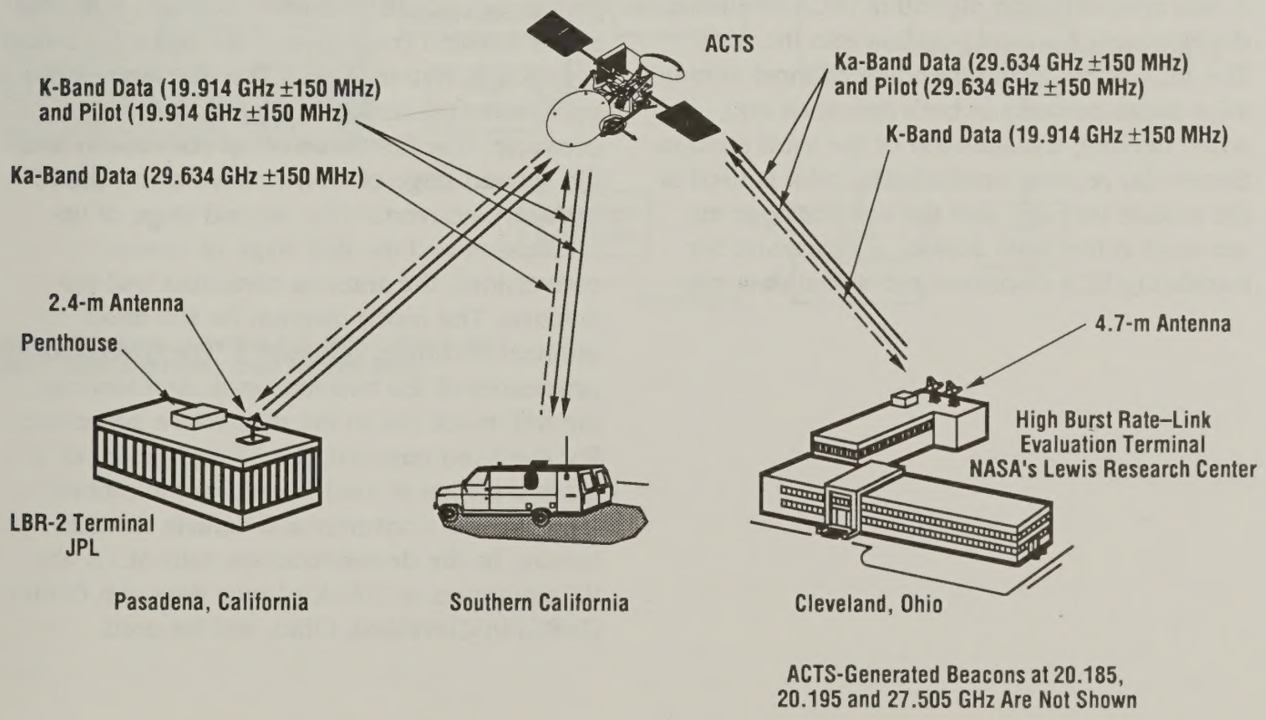
ACTS
K-Band Data (19.914 GHz ±150 MHz) and Pilot (19.914 GHz ±150 MHz)
Ka-Band Data (29.634 GHz ±150 MHz)
Ka-Band Data (29.634 GHz ±150 MHz) and Pilot (29.634 GHz ±150 MHz)
K-Band Data (19.914 GHz ±150 MHz)
2.4-m Antenna
Penthouse
4.7-m Antenna
High Burst Rate–Link Evaluation Terminal
NASA's Lewis Research Center
LBR-2 Terminal
JPL
Pasadena, California
Southern California
Cleveland, Ohio
ACTS-Generated Beacons at 20.185, 20.195 and 27.505 GHz Are Not Shown

Figure 1. AMT system setup.

transmitted. The data rate is selectable among 2.4, 4.8 and 9.6 kbps depending on channel conditions. A separate higher rate of 64 kbps will also be supported, but under restricted link conditions.

The AMT communication protocols adopted are consistent with the networking protocol framework developed under MSAT-X [5,6] and are designed specifically to be efficient in the mobile satellite environment. The AMT links are classified as open-ended (circuit-type links) for voice or long data transfers such as fax, or closed-ended (packet-type links) for short data transfers such as messages. Data transmission in either mode will be subject to acknowledgement and retransmission to ensure data integrity when required. The protocol constructs being designed extend the MSAT-X concepts to accommodate the additional requirements at Ka-band.

Operation at 20 and 30 GHz, particularly at the latter frequency, is susceptible to significant rain attenuation. To increase link availability and service continuity, all AMT links will be subject to data-rate selection or change as a function of any rain attenuation that may exist. Recent studies have indicated that under worst-month conditions, system availability can be improved from as low as 90% to above 99% [7]. A rain compensation algorithm (RCA) is under development for incorporation into the AMT. The RCA relies on independent channel attenuation measurements at both link ends and, when needed, transmission of the local attenuation to the remote terminal. The pilot is used at the mobile terminal and the satellite beacons are used at the fixed station. A procedure for translating RCA decisions into actual data-rate selection or change procedures is also being developed as part of the AMT communication protocol. These algorithms will reside in the terminal controller and will be explained later.

The absence of a pilot on the return link necessitates a creative solution to Doppler tracking on that link. Without compensation, the return link Doppler due to car motion can be as high as 3 kHz, with a rate up to 250 Hz/sec. In addition, uncertainties on the various oscillators along the link can accumulate about 1 kHz of frequency offset. The Doppler and frequency uncertainties can therefore be a significant fraction of the data rates at hand. In the AMT, the Doppler shift present on the pilot will be tracked at the mobile terminal, translated in frequency and used to precompensate (appropriately preshift) the data channel on the return link. This will achieve a significant performance enhancement at the fixed terminal and a reduction in the guard bands that would otherwise be required.

Mobile and Fixed Terminal Design

A block diagram of the AMT is shown in Figure 2. The diagram identifies the different subsystems as elements of the two broad divisions of the AMT — the baseband processor and the microwave processor. The baseband processor consists of a speech codec, a modem and a terminal controller; also attached is a data acquisition system (DAS). The elements of the microwave processor are the IF up/down converter (the first stage of up-conversion and the second stage of down-conversion), the RF up/down converter (the second stage of up-conversion and the first stage of down-conversion), the antenna controller and the antenna. The block diagram for the fixed terminal is shown in Figure 3. The baseband processors of the two terminals are identical; the difference lies in the microwave processor. For the fixed terminal, the RF equipment of a ground station is used instead of the mobile terminal's RF converter and vehicle antenna system. In the demonstrations with ACTS, the RF equipment at NASA's Lewis Research Center (LeRC) in Cleveland, Ohio, will be used.

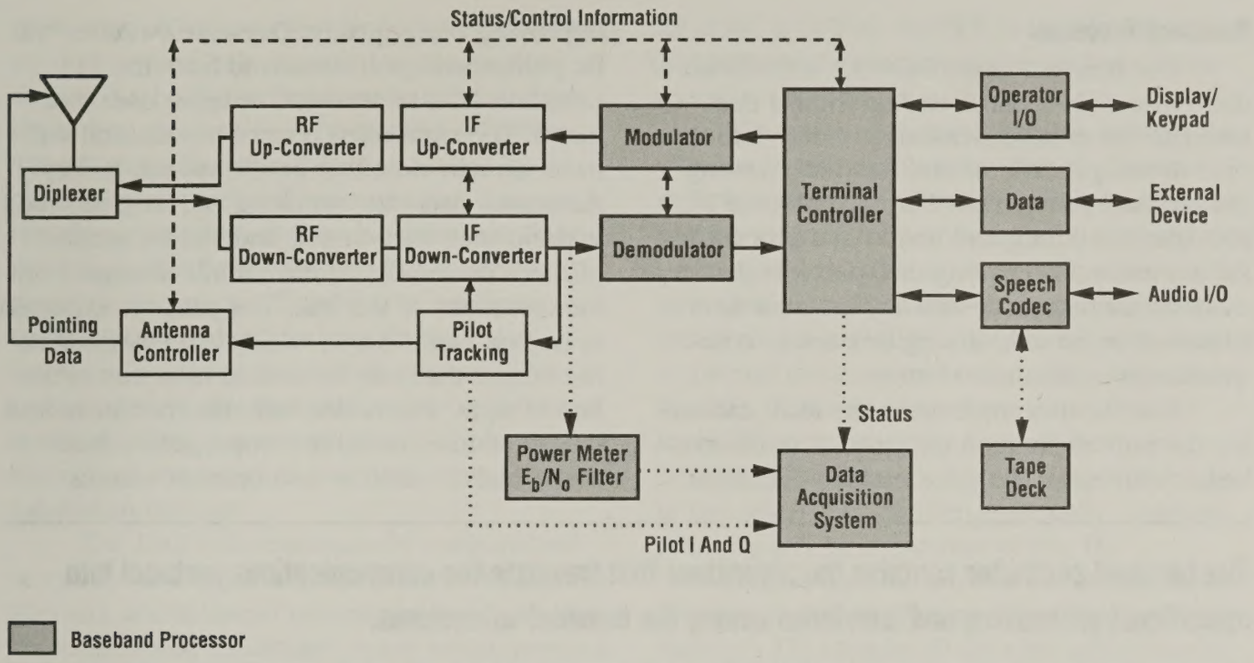

Figure 2. The ACTS mobile terminal.

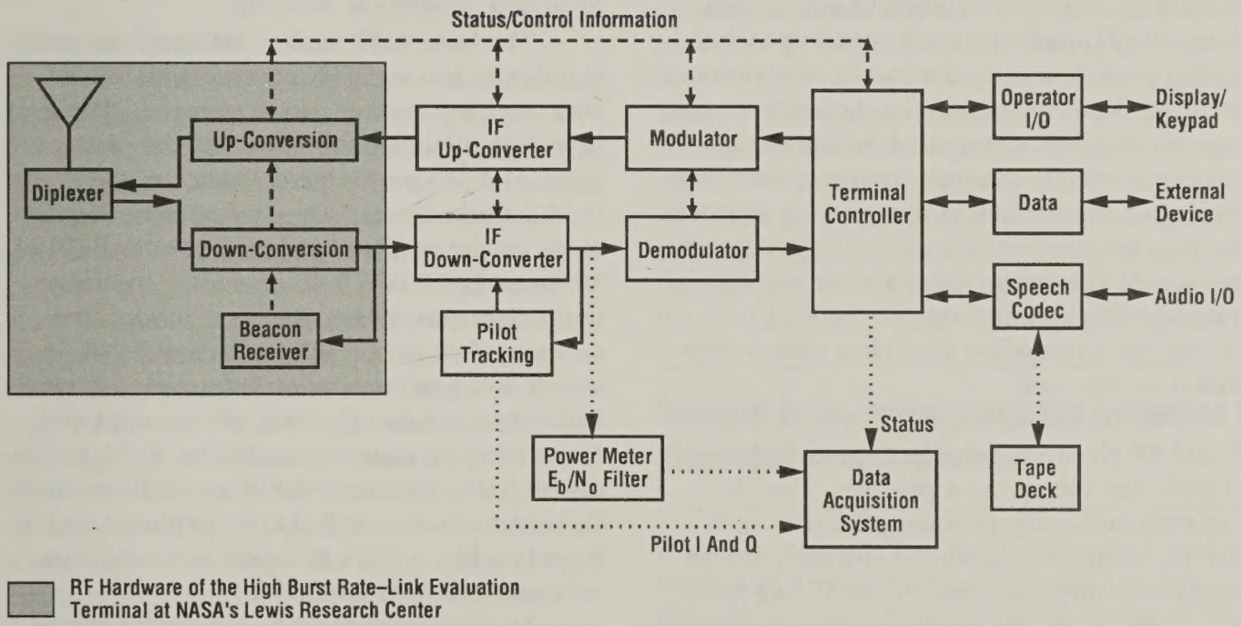

Figure 3. The fixed terminal version of the AMT.

Baseband Processor

The terminal controller (TC) is the brain of the terminal. It contains the algorithms that translate the communications protocol into the operational procedures and interfaces among the terminal subsystems. For example, the TC executes the timing and handshake procedures for the interaction among the speech codec modem, user interface and any external device (data source or sink) during link setup, relinquishment or data-rate change.

The TC also implements the RCA, extracting the rain attenuation information in its own beam from either the pilot tracking circuit (at the mobile terminal) or the beacon receiver (at the fixed terminal). Upon observing a certain amount of local attenuation and attenuation slope, the TC embeds in the digital speech a control packet to carry the locally obtained rain attenuation information and a data-rate change request. The remote terminal, which has its own local attenuation measurement, uses both sources of information and, according to stored decision rules, effects the appropriate data-rate change. At link setup, the initiating and responding TCs will also invoke the RCA to choose the appropriate data rates unless overridden by the user.

The TC also controls the operation of the IF and RF electronics and maintains high-level control over the antenna platform. The TC is also responsible for providing the user with a system monitoring capability and supports an interface to the DAS. Finally, the TC supports the test functions required during experimentation, such as bit stream generation, correlation and bit error counting.

The speech codec under development will convert inputted analog speech signals to a compressed digital representation at data rates of 2.4, 4.8 and 9.6 kbps, with monotonically improving voice quality. Data-rate switches will be performed upon command from the TC based on RCA information or upon user command. The embedded control information will have virtually no effect on the speech quality. Automatic data-rate switching will be performed with no user intervention and will be accomplished "on-the-fly" to have minimal impact on the continuity of the link. The pause is expected to be less than 0.5 sec, which is no worse than the outage that may be caused by a tree in the line of sight. The codec will also contain special design features to make its operation robust in the mobile satellite environment with its shadowing-induced outages. Finally, the codec will be capable of interfacing with the Public Switched Telephone Network.

The terminal controller contains the algorithms that translate the communications protocol into operational procedures and interfaces among the terminal subsystems.

The base AMT modem will implement a simple but robust DPSK scheme with rate 1/2 convolutional coding and interleaving. The goal here is to minimize the impact of the phase noise of ACTS on the performance of the modulation scheme.[1] The performance requirement for the modem is a bit error rate (BER) of 10^{-3} at an E_b/N_0 of 6.5 dB, including modem implementation losses. Alternate modulation schemes such as "pseudo-coherent" BPSK, in which link synchronization information is embedded in the data channel, will be explored. Depending on channel conditions, E_b/N_0 performance gains relative to DPSK could be realized. Coherent schemes will also be explored and, if found usable, will be included in a follow-on enhanced modem/transceiver.

In addition to the 2.4-, 4.8- and 9.6-kbps rates, the modem will be designed to handle up to 64 kbps for the possible demonstration of

[1] The ACTS communication payload possesses very low phase noise (–108 dBc/Hz) at frequency offsets of 1 MHz in keeping with the needs of high-rate communications. The payload, however, has high phase noise closer to the carrier (–52 dBc/Hz at 1 kHz), which is problematic for low-bit-rate communications.

slow scan (10 frames/sec) or compressed video on the forward link. Essential to the modem design is a built-in robustness to combat deep, short-term shadowing. The modem will "freewheel" through a signal outage caused by roadside trees and will reacquire the data as rapidly as possible after such a dropout. The modem is also being designed to handle possible frequency offsets due to oscillator uncertainties and drifts along the link. Any residual Doppler at the mobile terminal (not corrected through pilot tracking) or at the fixed terminal (after precompensation) will be estimated and corrected in the modem by Doppler estimation circuitry.

The DAS will continuously measure and record a wide array of propagation, communication link and terminal parameters (e.g., pilot and data signal and conditions, noise levels, antenna direction and vehicular velocity). The DAS will also provide real-time displays of these parameters to aid the experimenters in the field.

Microwave Processor

The vehicle antenna is the critical Ka-band technology item in the microwave processor. Two types of antennas are under development. The first is a "passive" reflector-type antenna to be used in conjunction with a separate high-power amplifier (HPA), and the second is an "active" array antenna with monolithic microwave integrated circuit (MMIC) HPAs and low-noise amplifiers (LNAs) integrated onto the array. Both antennas have their distinct advantages. The reflector is simpler and less risky to develop, but it requires a separate power amplifier. Such an amplifier could be an expensive or bulky item, which would not be attractive in a commercial terminal. The active array, despite being more complex and riskier to develop, uses MMIC technology to overcome the losses in the Ka-band hardware and obviates the need for a potentially expensive power amplifier, such as a TWT. The integration of the amplifiers also leads to a smaller, more conformal antenna assembly. With the mass market potential of Ka-band, the active array promises high performance at low cost. The design goals for the antenna system call for a minimum EIRP of 22 dBW, a G/T of –8 dB/K, a bandwidth of 300 MHz and a maximum size of 8 in. (diameter) by 3 in. (height).

The antenna pointing system enables the antenna to track the satellite for all practical vehicle maneuvers. Either of the two antennas will be mated to a simple yet robust mechanical steering system. This is one of the side benefits of migration to Ka-band — the considerably smaller mass and higher gain achievable relative to L-band make a mechanical dithering scheme feasible. Consequently, there is no need for lossy RF components to support electronic pointing. The necessary processing will reside in the antenna controller; eventually, antenna pointing will be a function of the TC.

On the transmit portion of the signal, the RF up-converter will convert an IF of approximately 3.373 GHz to 30 GHz for transmission; on the receive portion, the RF down-converter will convert the RF from 20 GHz down to the IF. The choice of the 3.373-GHz IF band is dictated by compatibility with the fixed station RF hardware to be used at LeRC during the demonstration (see Figure 3). For the passive antenna, the RF up-converter will also provide the antenna with sufficient power on the transmit signal to complete the communications link.

The IF up/down converter translates between 3.373 GHz and the 70-MHz IF at the output/input of the modem. A key function of the IF converter is pilot tracking and Doppler precompensation. The down-converted pilot is tracked in a phase-locked loop and used as a frequency reference in the mobile terminal. The tracked pilot is also processed in analog hardware and mixed with the up-converted data signal from the modem to preshift it in order to offset the Doppler on the return link. The IF converter provides the TC and antenna subsystem with pilot signal strength for the RCA and antenna pointing operation, respectively. Finally, the pilot in-phase and quadrature components are provided to the DAS for link characterization.

Essential to the modem design is a robustness to combat deep, short-term shadowing.

Experimental Setup With ACTS

The experimental setup for testing the AMT with ACTS is depicted in Figure 1. ACTS will be used in the microwave switch matrix (MSM) mode — i.e., as a bent-pipe repeater — to connect the fixed (hub) station with the mobile unit. Consistent with the ACTS frequency plan, the AMT uplinks will be at 29.634 GHz ±150 MHz and the downlinks at 19.914 GHz ±150 MHz. These bands coincide with the RF bands at which ACTS will be configured in the MSM mode to support the transmission of 220 Mbps. To simulate a hub station, the RF hardware of the High Burst Rate–Link Evaluation Terminal (HBR–LET), located at LeRC, will be mated with the AMT baseband and IF equipment, as depicted in Figure 3. The HBR–LET hardware utilized will comprise the 4.7-m antenna and the RF up/down conversion electronics to the 3.373-GHz interface.

Ka-band technologies will be demonstrated in 1993 and 1994 using the Advanced Communications Technology Satellite, a fixed terminal in Cleveland, Ohio, and a mobile terminal in Southern California.

The mobile terminal will be located in Southern California, allowing access to the satellite via its Los Angeles/San Diego (LA/SD) uplink and downlink beams. In the forward link, ACTS is commanded by the NASA Ground Station (NGS) at LeRC to receive signals from Cleveland on ACTS' fixed Cleveland beam and to route them to the transmit feeds of the LA/SD beam. The uplink signals will use one of ACTS' three transponders, e.g., transponder #1. The MSM will connect the output of receiver #1 to the HPA #1 and to the LA/SD feed of the ACTS downlink scanning beam. The scanning beam will be kept fixed over the LA/SD area for the duration of the experiment. Two signals, the data and the pilot, will be transmitted through the HBR–LET and will pass through the ACTS transponder. The effects of the limiter in the ACTS MSM have to be taken into account to obtain the correct link performance.

On the return link, ACTS will be commanded by the NGS to receive signals on the LA/SD beam feed of the ACTS uplink scanning beam (kept fixed) and to translate these signals to one of the other possible transponders, e.g., transponder #2. The MSM will connect the output of receiver #2 to the HPA #2 and hence to the Cleveland fixed beam feed. On the return link, the mobile terminal transmits only one signal (voice or data) through the transponder to the hub station.

As mentioned earlier, the AMT will implement data-rate change to enhance link availability during rain events. At the fixed terminal, uplink power control is also available. The measured rain attenuation of ACTS' Cleveland beam is obtained from the ACTS beacon receivers in the NGS located at LeRC. This input is used to control the drive level of the HBR–LET's TWT amplifiers. This uplink power control will be used to compliment the data-rate change capability of the AMT to compensate for rain on the forward link. Since the mobile terminal is limited in power, compensation for rain attenuation on the return link will rely solely on data-rate control. However, both the power control and data-rate changes performed on the forward and return links have to be effected in concert for proper system operation. This will be performed under the supervision of the AMT RCA, located in its TCs.

Figure 3 shows that the AMT fixed terminal will be combined with the HBR–LET RF equipment in Cleveland (or the Harris LBR-2 RF equipment if the LA–LA configuration is included). Unlike the mobile terminal, the fixed terminal will generate a pilot for transmission through the link. It will not perform pilot tracking since there is no pilot on the return link. The fixed terminal will interface with the

external power control capabilities of the HBR–LET and will receive beacon signal measurement information from the HBR–LET and the NGS as well. The RCA residing in the terminal controller of the fixed terminal will be assigned as the master over that in the mobile terminal if a master–slave data-rate control configuration is adopted.

At present, the baseline experiment includes only the LA/SD–ACTS–Cleveland (and vice versa) configuration. To facilitate debugging of the mobile-to-hub-station communication link, the possibility of obtaining a second fixed terminal for installation at JPL is being explored. This option is also included in Figure 1. This "JPL" terminal could utilize the RF equipment of the Harris LBR-2 terminal and would have three uses: (1) as a test-bed for the mobile terminal hardware being developed at JPL, (2) as a local hub station in lieu of the HBR–LET for initial system setup tests and (3) as a second "mobile" terminal for network tests when those follow-on tests are performed.

Conclusion

JPL is presently designing a Ka-band mobile terminal and is developing plans for a series of mobile experiments to explore the potential of Ka-band to meet the needs of future mobile satellite services. Two major technical challenges have been identified: maintaining the link in a demanding propagation environment and developing the enabling Ka-band technologies. The first challenge requires the development of data-rate and power control algorithms to compensate for rain fading; the design of a modem/transceiver capable of combating Doppler and frequency offsets while providing high power efficiency and robust resistance to shadowing, and the development of high-performance antenna tracking algorithms. The second technical challenge entails the development of antennas that are low cost, high performance, reliable and small in size. This will utilize Ka-band MMIC components and packaging techniques.

The land-mobile experiments using ACTS are scheduled to start in early 1993. The experiments will be centered around the goal of providing a more accurate characterization of the Ka-band channel and demonstrating its potential for mobile communications. Emphasis will be placed on assessing the efficacy of the system concepts, subsystem designs and technologies adopted in the AMT. These experiments should serve as a starting point for other mobile and micro terminal applications at Ka-band. It is hoped that the development of the AMT and the availability of ACTS will lead to other experiments and demonstrations of advanced land-mobile terminal hardware, maritime and aeronautical systems, hybrid satellite and land-based networks and, eventually, truly personal micro terminals.

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The ACTS Mobile Terminal Rain Compensation Algorithm

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The objective of the ACTS Mobile Terminal (AMT) rain compensation algorithm (RCA) is to ensure reliable operation in the forward and return satellite communications (SATCOM) link directions despite the possibility of uplink or downlink fading due to rain events in the vicinity of the fixed or mobile terminal (FT or MT). In particular, the RCA should maintain at least a 3-dB link margin at the highest possible transmission rate (9.6, 4.8 or 2.4 kbps). Although the RCA has been discussed in presentations at various stages of its evolution [1–3], it has never been formally documented; this article alleviates that oversight.

Discrete Multistate Fading Model

The initial concept of the RCA as proposed by Khaled Dessouky focused on a discrete 4-state fading model [4]. The states corresponded simply to the presence or absence of rain in the MT and FT. A cursory inspection of this model suggests that a binary characterization of the fading is inadequate to satisfy the objectives of the RCA. Ideally, the model should have separate states for various ranges of uplink and downlink rain attenuation to permit proper control of the data rate in 3-dB steps. However, even a partition of the fading state at the MT and FT into "light" and "heavy" rain will result in an impractical, complex 9-state model [2]. Consequently, our thinking shifted from a discrete to a continuous representation of the rain fading by means of a two-dimensional uplink and downlink attenuation plane, which is described below.

Two-Dimensional Continuous Fading Model

It is well known that the overall forward or return bent-pipe received carrier-to-noise ratio (CNR) is related to the uplink and downlink received CNRs by the inverse relationship [5]:

$$\left(\frac{C}{N_0}\right)_t^{-1} = \left[\frac{1}{A_u}\left(\frac{C}{N_0}\right)_u\right]^{-1} + \left[\frac{1}{A_d}\left(\frac{C}{N_0}\right)_d\right]^{-1} \quad (1)$$

where $(C/N_0)_t$ is the total received CNR, $(C/N_0)_u$ is the uplink received CNR in the absence of uplink rain attenuation A_u, and $(C/N_0)_d$ is the downlink received CNR in the absence of downlink rain attenuation A_d (all in absolute units rather than decibels at this point). If E_b is the received energy per bit and R_b is the data bit rate, the received signal-to-noise ratio (SNR) is

$$\left(\frac{E_b}{N_0}\right)_{recd} = \frac{1}{R_b}\left(\frac{C}{N_0}\right)_t \quad (2)$$

The AMT employs differential binary phase-shift-keyed (DBPSK) modulation with a (7,1/2) convolutional code. The SNR required to achieve the specified bit error rate (BER) of 10^{-3}, including a 0.75-dB allowance for modem implementation losses, is 6.50 dB [6]. The difference in dB between the received and required SNRs is the performance link margin μ in dB, which is given by

$$\mu = \left(\frac{C}{N_0}\right)_t - 10 \log_{10} R_b - 6.5 \qquad (3)$$

where $(C/N_0)_t$ is now in dB-Hz and R_b is in bps. Although Equation (3) clearly shows that μ varies on a one-to-one basis with $(C/N_0)_t$ in dB-Hz, Equation (1), in turn, illustrates that its dependence on A_u and A_d is nonlinear. Equation (3) also includes a one-to-one relationship between μ and R_b in dB-Hz, which we will retain throughout this article although it ignores any modem implementation losses.

The AMT return link has a much lower performance margin than the forward direction and is, therefore, more susceptible to rain attenuation dropouts. In Table 2 of [6], the margin at 9.6 kbps in the absence of fading (i.e., $A_u = A_d = 0$ dB) is shown as 5.15 dB. (This is a combination of the 2.65-dB margin at the bottom of Table 2 and the 2.50-dB fade allowance.) This margin occurs with $(C/N_0)_d = 73.90$ dB-Hz and $(C/N_0)_t = 51.47$ dB-Hz, which implies from Equation (1) that $(C/N_0)_u = 51.49$ dB-Hz. As A_u or A_d rises above 0 dB due to rain near the MT or the FT, respectively, $(C/N_0)_t$ will fall, as will μ, on a one-to-one basis. If the RCA needs to maintain a minimum link margin of 3 dB, it should drop R_b to 4.8 kbps when $(C/N_0)_t$ reaches 49.32 dB-Hz, which will cause μ to jump to 6 dB. Similarly, when $(C/N_0)_t$ drops to 46.32 dB-Hz due to increased rain fading, R_b should be lowered to 2.4 kbps.

These data-rate change (DRC) boundaries are shown in the A_u–A_d fade plane of Figure 1, which also illustrates the nonlinear relationship between A_u and A_d for fixed μ. (The dashed boundary in Figure 1 corresponds to the lowest data rate; beyond this region, the rain fading is too severe to sustain the desired RCA objective, $\mu \geq 3$ dB.)

Using Equations (1–3), the equations for the DRC boundaries are given parametrically by Equation (4), where A_u and A_d are in dB, $(C/N_0)_u = 51.49$ dB-Hz, $(C/N_0)_d = 73.90$ dB-Hz, $\mu = 3$ dB and $R_b = 9{,}600$, 4,800 and 2,400 bps.

$$A_u = \left(\frac{C}{N_0}\right)_u + 10 \log_{10} \left(10^{-\frac{1}{10}[\mu + 6.5 + 10 \log_{10} R_b]} - 10^{-\frac{1}{10}\left[\left(\frac{C}{N_0}\right)_d - A_d\right]} \right) \qquad (4)$$

If, for the moment, we ignore the problem of jointly estimating A_u and A_d, along with the impact of the fade slope (i.e., dA_u/dt and dA_d/dt) information, the RCA in the AMT terminal controller (TC) would simply select R_b according to the nonlinear boundaries in Figure 1. However, we could also consider piecewise-linear approximations to these DRC boundaries as shown in Figure 2.

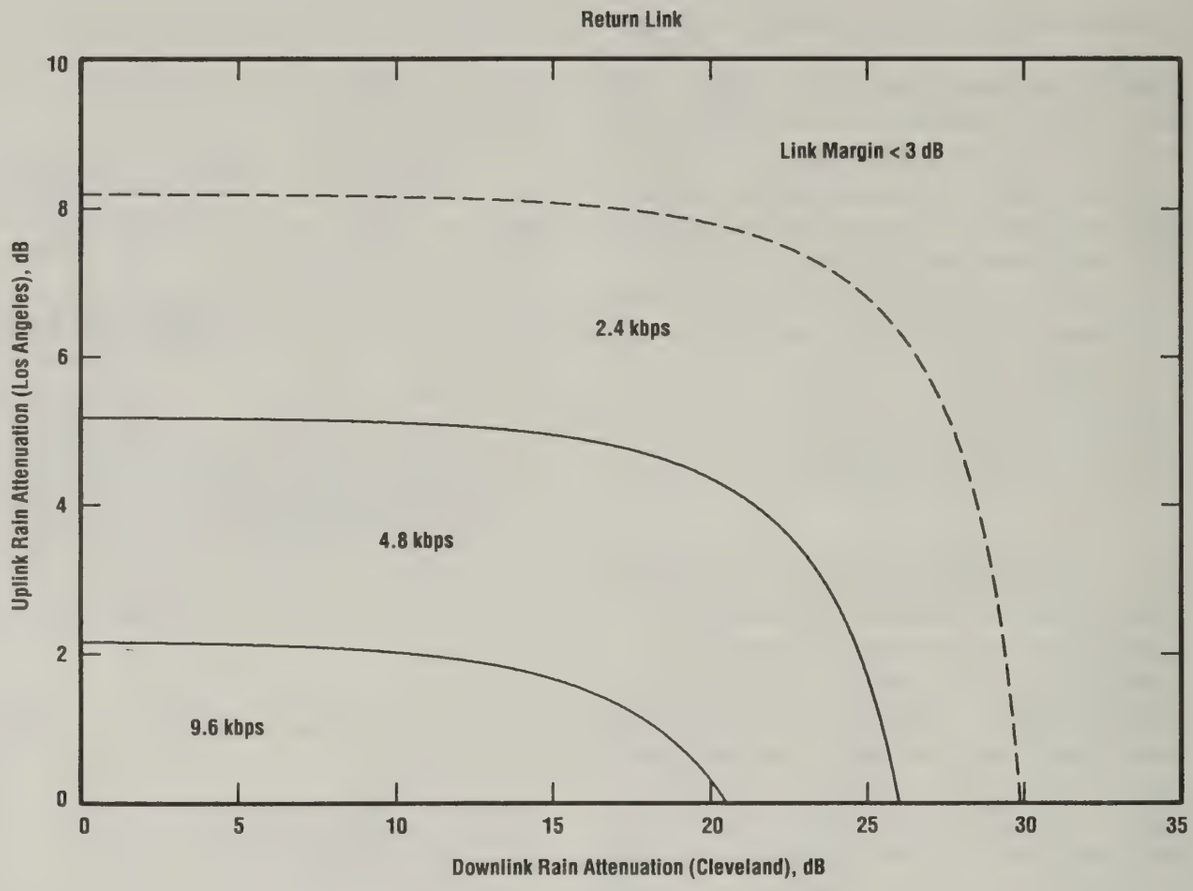

Figure 1. DRC boundaries as a function of A_u for an MT in Los Angeles and A_d for an FT in Cleveland such that the AMT return link margin $\mu \geq 3$ dB for $R_b \geq 2.4$ kbps.

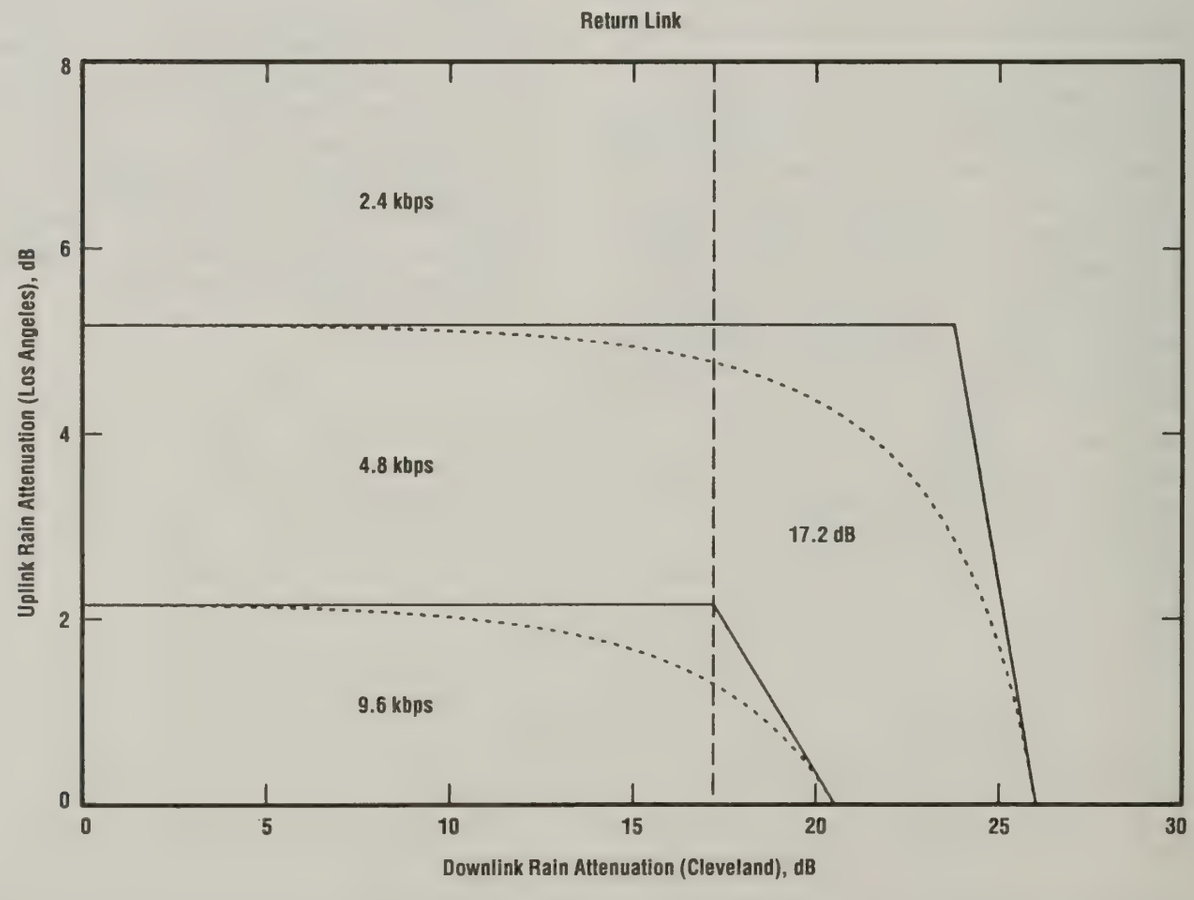

Figure 2. Piecewise-linear approximations to DRC boundaries in Figure 1.

One-Dimensional Fading Model

Because $(C/N_0)_u$ is 22.4 dB less than $(C/N_0)_d$, Equation (1) shows that the return link margin is much more sensitive to A_u than to A_d. This observation, illustrated in Figures 1 and 2, is *independent of the location of the MT.* This suggests a further simplification to the return link RCA: If it can be argued that it is highly improbable that A_d will exceed 17.2 dB (the lower of the two break points for the piecewise-linear approximate DRC boundaries in Figure 2) for an FT in Cleveland, the selection of R_b by the TC could effectively be based only on A_u. A rain attenuation model based on annualized rainfall statistics developed by R. M. Manning of the Lewis Research Center [7] can be used to show that the rain attenuation for an ACTS terminal in Cleveland will be less than 17.2 dB 99.98% of the time. Even if these results are extended to the worst-month averaged rainfall statistics [8], they will still fall left of the vertical dashed line in Figure 2, with a probability of 99.92%. Such a high probability justifies the following *one-dimensional* return link RCA:

$$R_b = \begin{cases} 9.6 \text{ kbps}; & A_u < 2.15 \text{ db} \\ 4.8 \text{ kbps}; & 2.15 < A_u < 5.17 \text{ dB} \\ 2.4 \text{ kbps}; & A_u > 5.17 \text{ dB} \end{cases} \quad (5)$$

The data-rate profile and the corresponding return link margin characteristic are shown in Figure 3 as a function of A_u.

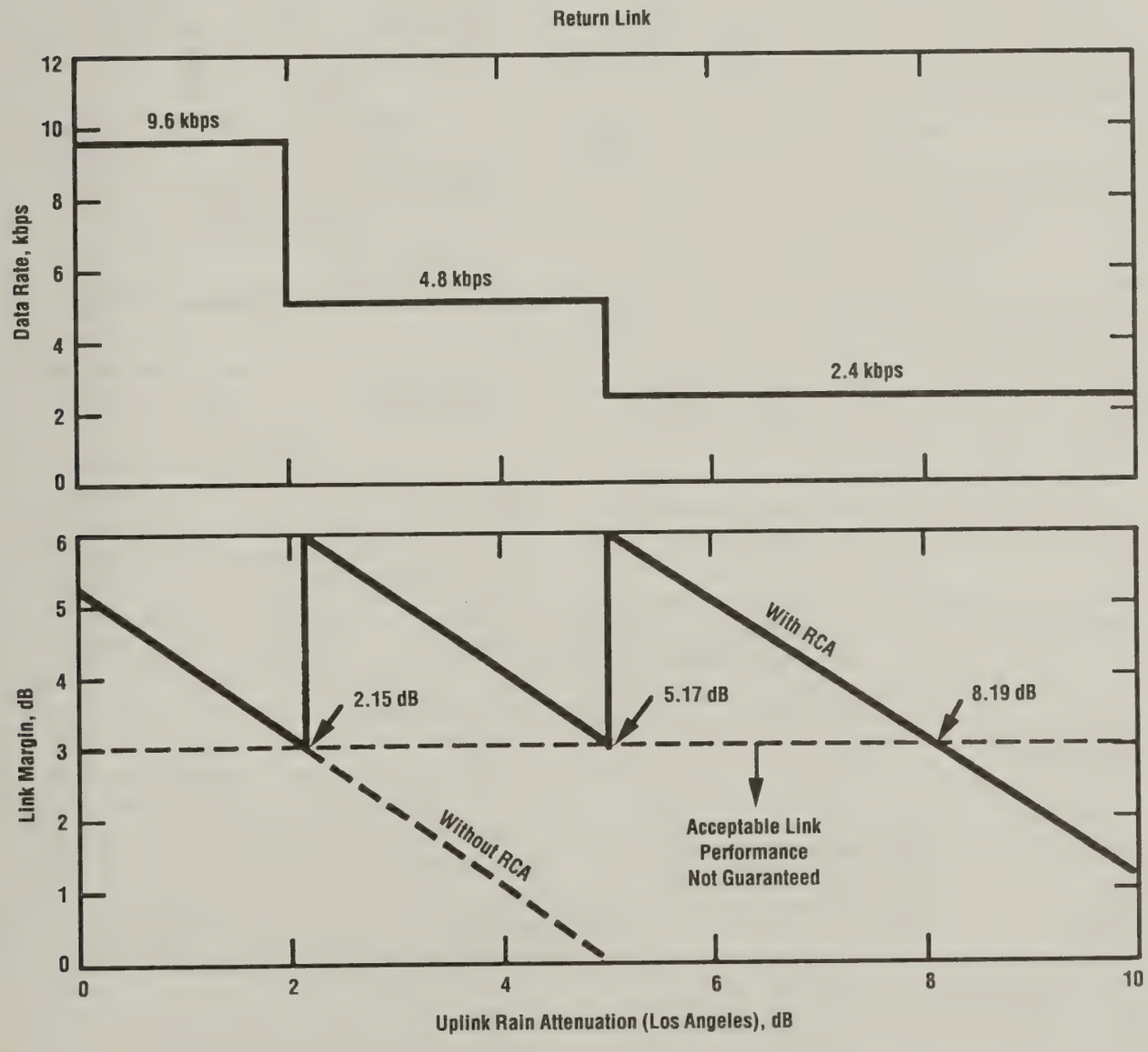

Figure 3. Return link DRC profile based on approximate, one-dimensional RCA.

The operation of this simplified RCA is illustrated for a hypothetical uplink rain attenuation timeline in Figure 4. In this example, the two basic categories of rain events are shown: stratiform or light rain showers and convective or heavy thunderstorm and cloudburst activities. Convective events are characterized at their onset by relatively steep fade slopes (as high as 1–2 dB per second, although typically an order of magnitude lower) with slower recoveries as the rain abates; if dA_u/dt is measured along with A_u, the intermediate 4.8-kbps data rate can be bypassed for sufficiently large fade slopes, as shown in Figure 4. Also, if the rain attenuation exceeds 8.19 dB, the return link margin will fall below 3 dB, and the corresponding performance will deteriorate accordingly; this is usually referred to as a dropout.

The link availability is defined as the probability that the link margin lies above 3 dB, or 1-Pr [dropout]. As shown in Figure 3, without the RCA, a dropout would occur whenever A_u exceeds 2.15 dB; with the one-dimensional RCA, this threshold is relaxed to 8.19 dB. If Manning's rain attenuation model for an MT in Los Angeles, California, and Portland, Maine (Portland was selected because of its significantly higher rain rates and because the AMT is intended to demonstrate Ka-band mobile SATCOM capabilities throughout the contiguous United States) is modified empirically to correspond to the worst rainfall month in each locale [7,8], the advantages of even this simplified RCA are evident in Table 1. Under worst-case rain conditions, a 98% or greater link availability is generally tolerable for a mobile SATCOM system; lower availability levels would tend to be annoying to most users.

Table 1. Improvement in return link performance due to one-dimensional RCA as measured by worst-month availability

MT location	Return link availability using worst-month statistics, %	
	Without RCA	With RCA
Los Angeles, CA	97.2	99.7
Portland, ME	90.5	98.1

The AMT forward link RCA is similar, albeit with different DRC regions. From Table 1 in [6], the forward link margin at 9.6 kbps in the absence of fading is 18.83 dB, which is 13.68 dB better than the return link margin. The forward link DRC boundaries in the A_u–A_d fade plane corresponding to Figure 1 for the return link are shown in Figure 5. As in the return direction, the RCA is essentially only dependent on the rain attenuation in the ACTS–MT leg of the SATCOM bent-pipe, which is A_d in the forward direction. The insensitivity of the forward link DRC boundaries to A_u is further accentuated if we include the impact of transmission power control in the FT. The one-dimensional forward link RCA specification equivalent to Equation (5) is

$$R_b = \begin{cases} 9.6 \text{ kbps}; & A_d < 15.83 \text{ db} \\ 4.8 \text{ kbps}; & 15.83 < A_d < 18.84 \text{ dB} \\ 2.4 \text{ kbps}; & A_d > 18.84 \text{ dB} \end{cases} \quad (6)$$

Therefore, the 13.68-dB margin advantage translates on a one-to-one basis into an increased tolerance to rain attenuation.

Rain Fade Measurement and Frequency Scaling

Let us now consider the rain fade estimation problem. If, for now, we are satisfied with the simplified forward and return direction RCAs, based on the one-dimensional fading model, we need to measure the frequency-dependent rain attenuation in the ACTS–MT 19.91-GHz forward downlink and the 29.63-GHz return uplink. The easiest way to accomplish this is to monitor the power in the 19.91-GHz ACTS pilot received by the MT. Variations in this power level correspond precisely to the temporal behavior of the forward downlink rain attenuation since the frequencies are identical. To minimize the adverse impact of measurement noise, the received pilot level should be lowpass filtered or time-averaged. The one-way propagation time for a geostationary satellite bent-pipe link is on the order of 0.25 sec, excluding additional system processing delays; it would take a similar amount of time to notify the other end of the link of any DRC. So the

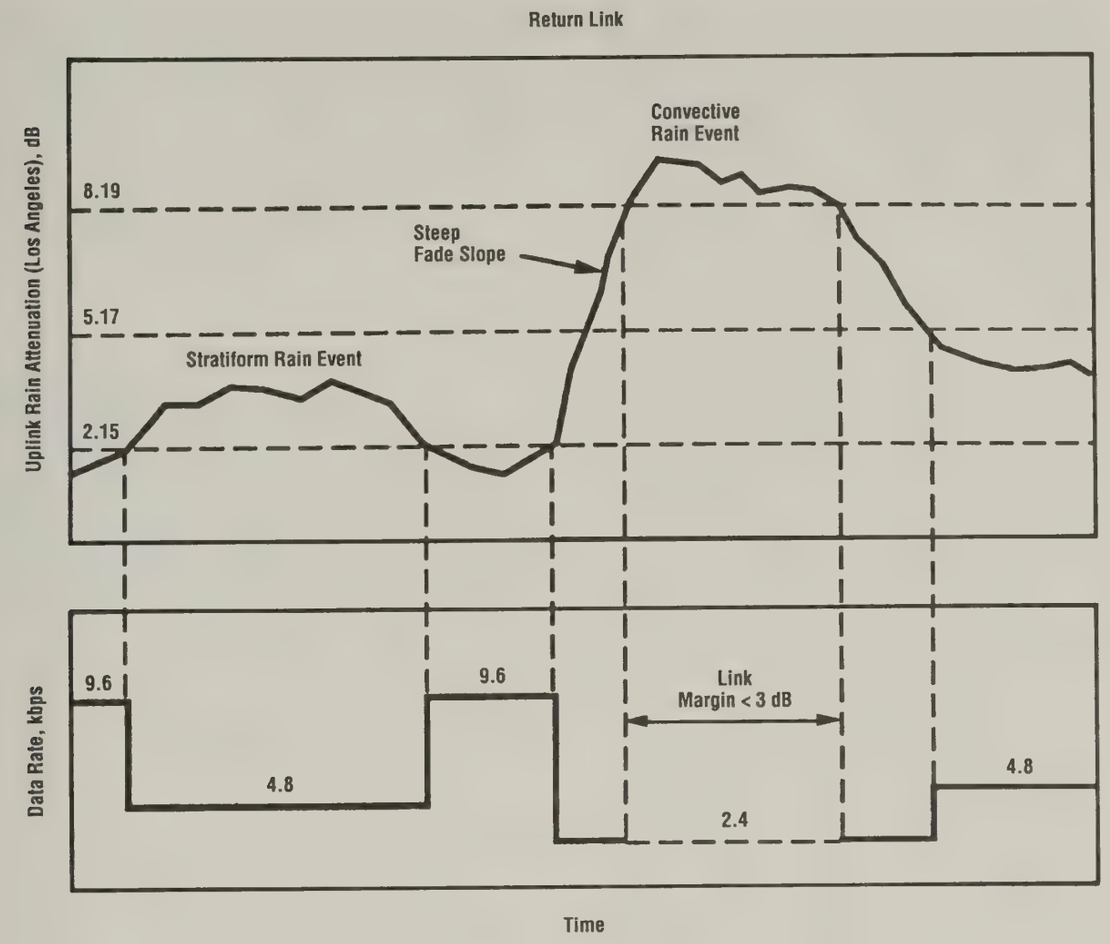

Figure 4. An example of the operation of the simplified return link RCA that depends only on the variation of A_u assuming no measurement noise.

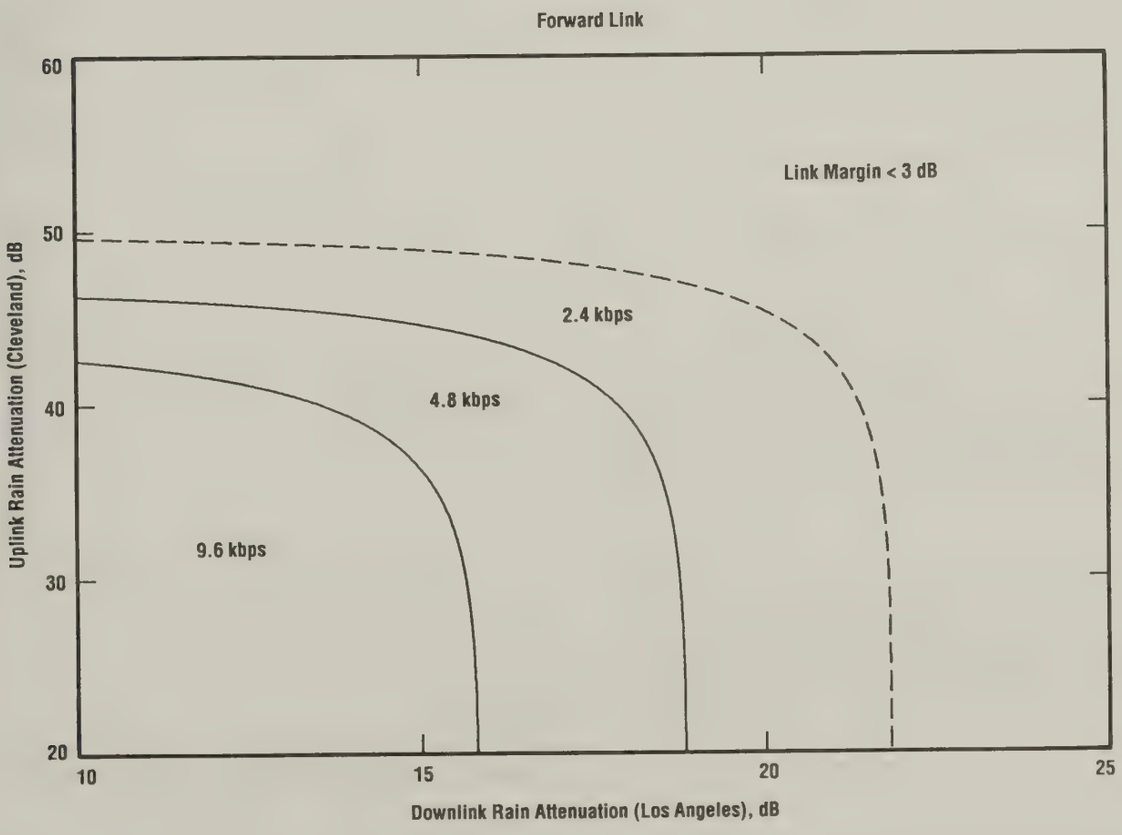

Figure 5. DRC boundaries as a function of A_u for an FT in Cleveland and A_d for an MT in Los Angeles subject to an AMT forward link margin $\mu \geq 3$ dB when $R_b \geq 2.4$ kbps.

RCA cannot respond to fade events of less than about 1 sec in duration. In the case of the MT, this applies to singular shadowing events of the same duration, i.e., an RCA based on 1-sec fading averages would be insensitive to shadowing caused by a small number of trees or telephone poles. (For example, at 55 mph, the MT travels about 80 ft in 1 sec.) In fact, recent rain attenuation measurements made by the Virginia Polytechnic Institute using the Olympus satellite beacons suggest that a 5–10-sec averaging time is needed to smooth out fluctuations due to cloud scintillation effects [9]. Since we do not want to add too much overhead to the AMT communication system, a 5-sec periodic update of the ACTS–MT link fading based on an average of the received pilot strength since the previous update is satisfactory; if the pilot measurement SNR with 5-sec averaging is a little low, we can easily extend it to 10 sec.

For the return uplink, we need to perform a frequency scaling operation. Since the instantaneous rain attenuation in the ACTS–MT link depends on the frequency but not on the direction of transmission, we will denote the forward downlink attenuation by A_{20} (nominal 20 GHz) and the return uplink by A_{30}. Virginia Polytechnic Institute has experimented with linear and log-linear empirical scaling formulas of the form [10][1]:

$$A_{30} = c_1 + c_2 A_{20}$$
$$\ln(A_{30}) = c_3 + c_4 \ln(A_{20}) \qquad (7)$$

An alternative approach has been suggested by Manning [11]. He previously argued in [7] that the rain attenuation A (dB) for a link with propagation length L (km) passing through the approximately 4-km-high rain belt above Earth is the integral of the specific attenuation Γ (dB/km):

$$A = \int_0^L dl\ \Gamma(l) \qquad (8)$$

Equation (9) shows Manning's rain attenuation model applied to the ACTS–MT link geometry when the MT in Los Angeles yields L = 6.15 km; Γ is frequency-dependent and related to the rain rate R (mm/hr) at a given location by the empirical formula in [12]

$$\Gamma = a(f)R^{b(f)} \qquad (9)$$

where $a(f)$ and $b(f)$ are specified in Table 2 for the AMT frequencies of interest.

Since $\Gamma(l)$ is approximately constant over L, Equations (8,9) reduce to

$$A(f) \approx La(f)R^{b(f)} \qquad (10)$$

which implies that the 20–30-GHz frequency scaling relationship for Los Angeles can be approximated by

$$A_{30} \approx La_{30}\left(\frac{A_{20}}{La_{20}}\right)^{\frac{b_{30}}{b_{20}}} = 2.45\ A_{20}^{0.936} \qquad (11)$$

where A_{20} and A_{30} are in dB. This scaling formula is plotted in Figure 6. If we take the

[1] Actually, Virginia Polytechnic Institute included terms on the right side of both equations in Equation (7) to account for the 12-GHz Olympus beacon, but they discovered that this additional factor increased the maximum deviation between the calculated and measured values of A_{30}.

natural logarithm of both sides of Equation (11), we derive Virginia Polytechnic Institute's log-linear relationship in Equation (7). Since Manning's model is approximate (the 4-km-high rain belt that determines L is particularly suspect), Equation (11) may need to be parametrically refined based on our own AMT observations.

Variable	f (frequency)	
	19.91 GHz	29.63 GHz
$a(f)$	0.0586	0.1534
$b(f)$	1.117	1.046

Table 2. Empirically determined values of frequency-dependent parameters [see Eq. (9)] for the ACTS mobile terminal uplinks and downlinks

Impact of Fade Slope Data on the RCA

We can process the received pilot strength to derive a sequence of 5-sec averages of the forward downlink and the frequency-scaled return uplink rain attenuations using the approach described above. For example, denote the averaged return link sequence by $\{\ldots A_u(t_1), A_u(t_2), A_u(t_3), \ldots\}$ for arbitrary time instants $\{\ldots t_1, t_2, t_3, \ldots\}$ spaced 5 sec apart. We can approximate $A_u(t)$ by 5-sec piecewise-linear segments with endpoints given by the previous sequence. And we can predict the fade slope for the interval (t_2,t_3) at t_2 by simply extrapolating the fade slope for (t_1,t_2), which allows us to predict $A_u(t_3)$ at t_2 by the formula

$$\hat{A}_u(t_3) \approx 2A_u(t_2) + A_u(t_1) \qquad (12)$$

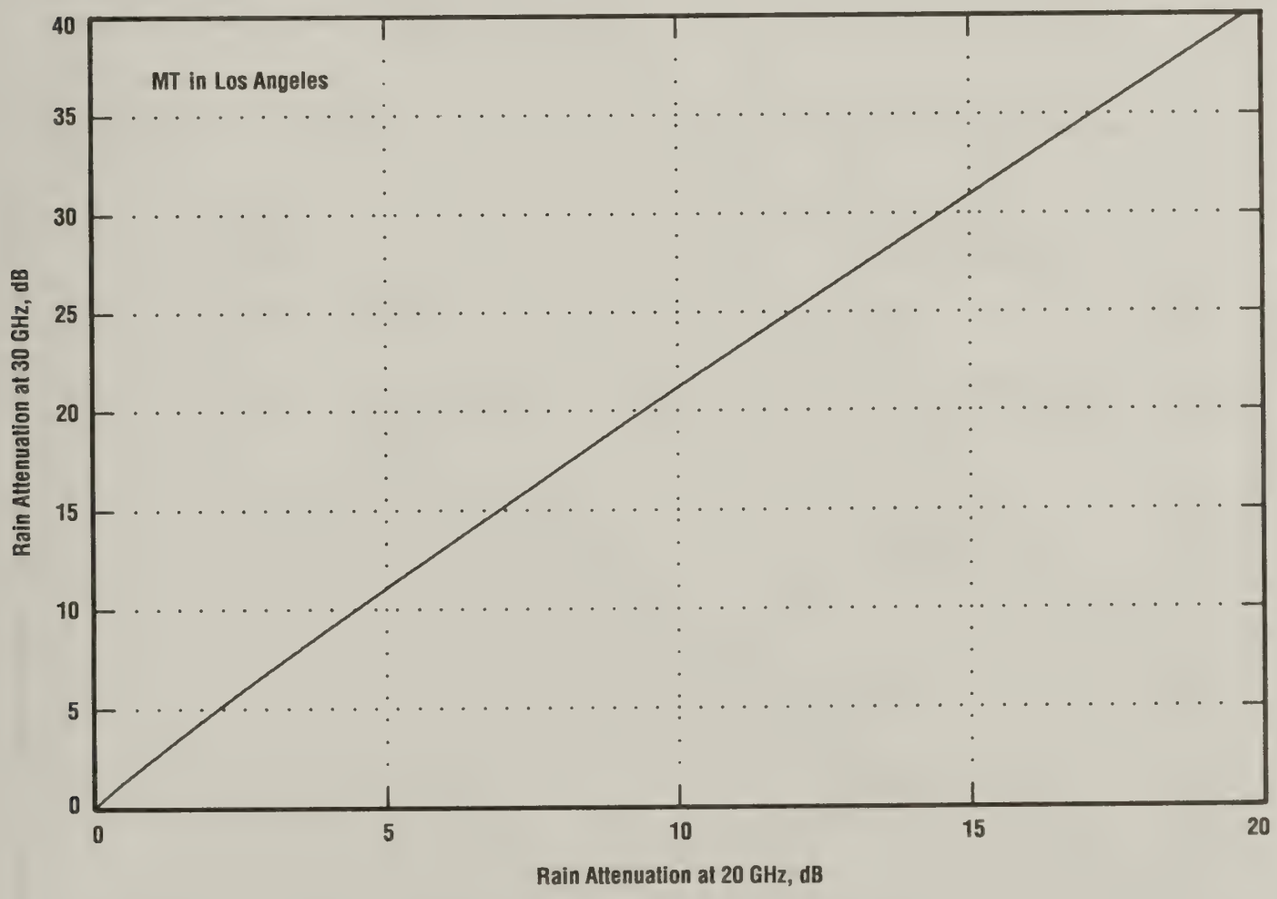

Figure 6. Approximate empirical relationship between rain attenuation at 20 and 30 GHz for the ACTS–MT link when the MT is in Los Angeles.

As an example, the simplified RCA of Equation (5) determined R_b for (t_2, t_3) based only on $A_u(t_2)$. But if the prediction specified by Equation (12) indicates that at some point during (t_2, t_3) the return link margin may fall below 3 dB, we want to decrease R_b at t_2 rather than waiting until t_3. As shown in the piecewise-linear plot of $A_u(t)$ in Figure 7, the largest attenuation anticipated at t_2 for the next 5-sec interval is given by the larger of $A_u(t_2)$ and $\hat{A}_u(t_3)$. Consequently, the RCA should be modified so that R_b for (t_2, t_3) is given by the prescription

$$R_b(t_2,t_3) = \begin{cases} 9.6 \text{ kbps; } \max[A_u(t_2),\hat{A}_u(t_3)] < 2.15 \text{ db} \\ 4.8 \text{ kbps; } 2.15 < \max[A_u(t_2),\hat{A}_u(t_3)] < 5.17 \text{ dB} \\ 2.4 \text{ kbps; } \max[A_u(t_2),\hat{A}_u(t_3)] > 5.17 \text{ dB} \end{cases} \quad (13)$$

This fade/fade slope RCA could cause the data rate to change from 9.6 kbps directly to 2.4 kbps for sufficiently steep fade slopes as illustrated in Figure 4.

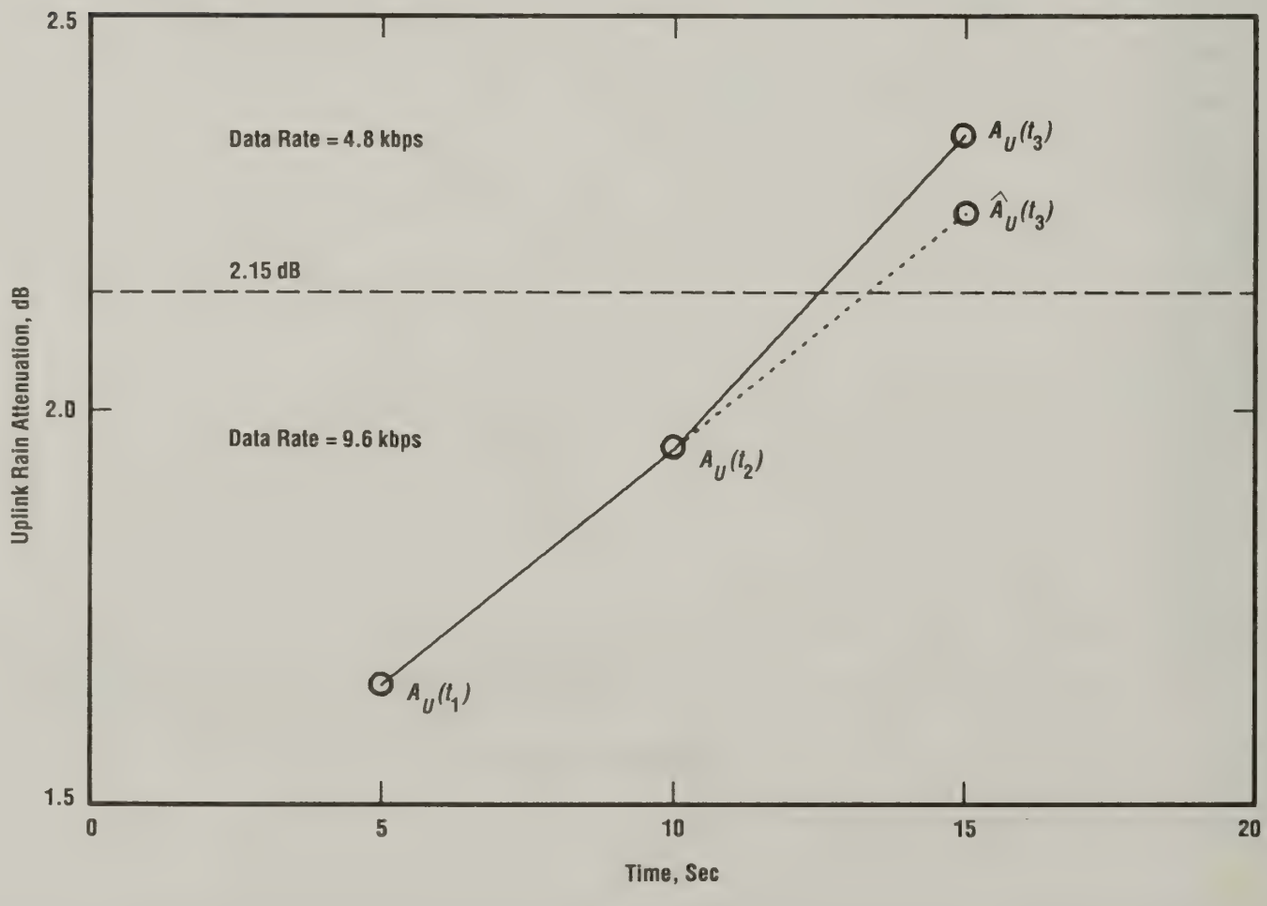

Figure 7. Piecewise-linear recreation of uplink rain fade process based on frequency-scaled 5-sec averages of received pilot attenuation; dashed line shows extrapolated fade slope prediction.

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Digital Audio Broadcasting Demonstrated in Las Vegas

Randy Cassingham, SATCOM Quarterly *Editor*
Jet Propulsion Laboratory

"We're listening to the future," a conventioneer said to a companion, speaking for many. On a specially equipped bus driving a predetermined route through downtown Las Vegas, conventioneers listened to an over-the-air demonstration of digital audio broadcasting (DAB). The demonstration was offered during the National Association of Broadcasters (NAB) Convention, held April 14–18, 1991, at the Las Vegas Convention Center, and was sponsored by the NAB, the Eureka-147 DAB Project and the European Broadcasting Union.

The event marked the first U.S. broadcast demonstration of the Eureka-147 digital broadcasting system. Developed by the Eureka-147 DAB Project, a consortium of European broadcasters, manufacturers and research institutes,[1] the Eureka system can be used for terrestrial, satellite or mixed broadcasting systems. The system is unique, according to the consortium partners, because of its "new channel coding and modulation scheme, known as Coded Orthogonal Frequency Division Multiplex."

Demonstration Setup

The Eureka system used in Las Vegas consisted of a single transmitter capable of providing 12 channels of stereo programming in 3.5 MHz of bandwidth. Each program channel is rated at 256 kpbs (128 kbps each for the left and right stereo sides). For the demonstration, nine of the 12 channels carried programming; eight were from digital tape recorders and one was a simulcast of a local radio station. Under a temporary experimental license issued by the Federal Communications Commission, the digital signal was transmitted at 479 MHz; normally assigned to UHF television broadcasts, this channel is not used in the Las Vegas area. The transmitter's power output was 30 W effective radiated power (ERP). A 10-dB-gain television antenna was used to transmit the digital signal.

To provide a signal comparison, a standard 30-W ERP stereo FM analog radio transmitter simulcasted one of the DAB programs at 94.9 MHz. The FM and DAB transmit antennas were located side-by-side at the top of the Hilton hotel, next to the convention center. Omnidirectional receiving antennas were used on the bus; the FM receiver was a standard car radio, and the DAB receiver was one of the five digital receivers built so far by the Eureka-147 DAB Project.

In addition to the primary Eureka-system transmitter on the Hilton, a 1-W gap-filler transmitter was mounted atop the Golden Nugget casino in the downtown area. Normally, by receiving the digital signal and retransmitting it at the same frequency, the gap filler provides coverage in areas shadowed from the primary DAB transmitter. For the demonstration, however, the gap filler's function was to provide a strong multipath signal to compete with the primary transmitter. An interference monitor on the bus clearly showed the relative signal

[1] The partners are Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR); AEG Mobile Communication GmbH; British Broadcasting Corporation; Centre Commun d'Etudes de Télédiffusion et Télécommunications; Deutsche Bundespost Telekom; Fraunhofer Gesellschaft, IIS; Grundig AG; Institut für Rundfunktechnik GmbH; Intermetall, Halbleiterwerk der Deutsche ITT Industries; Nederlandse Philips Bedrijven B.V.; Philips Electronique Grand Public; Robert Bosch GmbH; TCE, Deutsche Thomson-Brandt GmbH, and Telefunken Sendertechnik GmbH.

strengths; the gap-filler signal could easily be seen on the monitor and was at times stronger than the primary signal. No such artificial multipath generator was needed for the FM signal; the downtown buildings created enough natural multipath to seriously degrade the FM signal.

Comparison of Digital Audio, FM and AM Broadcasts

During the 30-minute ride from the convention center to downtown and back, the Eureka-system demonstrator, controlling the system from the back of the bus, switched back and forth between the digital transmission and the simulcasted FM signal. Near the convention center, a practiced ear was needed to notice the difference in quality between the signals (the digital signal had a greater dynamic range). But downtown, thanks in part to the high-quality Sennheiser HD 450 headsets provided to each listener, even the most amateur ear could hear the difference in quality between the FM and digital signals. The FM signal suffered greatly from multipath; fades and loss of stereo separation were frequently heard. However, the effects of multipath and phase distortion were completely eliminated on the digital receiver.

According to the demonstrator, when the gap filler's signal was stronger than the primary signal, the DAB receiver used the reflected signal to pull in program data. This "creative" use of multipath was DAB's greatest strength, we were told; rather than adding distortion to the signal, as with conventional FM broadcasting, multipath actually helps to eliminate dead spots in coverage. This additional coverage is necessary, considering the high frequencies likely to be allocated for digital broadcasting. As could be expected from a public demonstration, at no time did the bus go outside the DAB transmitter's coverage area; no signal distortions or losses were noted on the DAB system.

To provide an even more realistic comparison between digital and conventional broadcasting, a local radio station (KLUC) was used. KLUC simulcasts its programming at 1140 kHz AM and 98.5 MHz FM. Via a pair of telephone lines, KLUC's programming feed was also routed to the DAB transmitter at the Hilton and broadcast digitally. While downtown, we were able to listen to the same program on AM, FM and DAB. The differences between the AM and FM signals were obvious; the differences between the FM and DAB signals were less clear, but considering the DAB transmitter's 30-W ERP signal and KLUC's high-power broadcast signal, this lack of difference in broadcast quality was notable.

In a 30-minute demonstration in Las Vegas, the Eureka-147 digital broadcasting system completely eliminated the effects of multipath and phase distortion. The digital receiver actually used a multipath signal to pull in program data and eliminate dead spots in coverage.

Regulatory Concerns

Digital broadcasting was discussed at several NAB Convention conference sessions. The NAB clearly recognizes that digital broadcasting is the wave of the future; one NAB brochure states that "to stay competitive with its other audio competitors, radio must prepare to transmit digitally." The Association, however, is apparently against direct satellite broadcasting and insists that terrestrial broadcasting is preferable, as satellite transmissions will interfere with "local programming and diversity afforded by terrestrial DAB. [Furthermore,] satellites are

not spectrum efficient. . .Satellite DAB would undermine the audience size and financial viability of local stations."

One session was devoted entirely to nonterrestrial digital broadcasting. The emphasis was not on satellites versus terrestrial transmissions, but on how the two can be most effectively integrated. The panelists with international contacts made it plain that satellites will be the primary carriers of signals in many countries, no matter what the United States does domestically.

According to both a NAB study and a Canadian study, approximately 60 MHz of spectrum will be needed for a terrestrial-only DAB system in North America; about 76 MHz will be required for a mixed satellite–terrestrial scheme. Most proponents of DAB are hoping that L-band (1.5 GHz) will be allocated for digital broadcasting — for both satellite and terrestrial transmissions. There are concerns on some fronts, however, whether DAB will fare well against other L-band interests, such as aeronautical navigation. Alternative proposals call for allocations in the region of 800 MHz and in S-band (around 2.4 GHz). DAB allocations will be an important topic at the World Administrative Radio Conference in Torremolinos, Spain, in February and March 1992.

NASA and the Voice of America are planning the world's first demonstration of direct-to-mobile digital satellite broadcasting for later this year. The goal is to broadcast at a data rate of 19 kbps, providing AM-quality sound.

Satellite Demonstration Planned

NASA, in association with the Voice of America, is planning the world's first demonstration of direct-to-mobile digital satellite broadcasting for later this year. Because of existing satellite power limitations, the goal is to demonstrate DAB at a data rate of approximately 19 kbps, which would provide approximately AM-quality sound.

This demonstration will not attempt to duplicate CD-quality sound. "A number of applications, such as news or educational programming, can have their broadcast needs met without CD quality," says Ann Heyward of NASA's Lewis Research Center, who is heading the demonstration effort. Indeed, much of Voice of America's programming is currently on shortwave bands; a moderate-rate digital signal could provide a significant improvement in sound quality.

JPL will supply the ground-based equipment for the demonstration. A vehicle equipped with JPL's active tracking antenna, developed for MSAT-X studies, will be used to gather reception data in various environments. After initial experimental trials in Connecticut, the demonstration will take place in the Washington, D.C., area. The INMARSAT MARECS-B2 satellite will be the broadcast platform.

JPL has been studying potential UHF and L-band direct-to-user digital satellite broadcasting systems, considering program reception by both portable and mobile receivers. JPL's efforts in this area are described in more detail in the following article.

Direct Broadcast Satellite–Radio Studies at JPL

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The 1992 World Administrative Radio Conference (WARC) will consider a frequency allocation to the Broadcasting Satellite Service (BSS) (Sound). As part of its contract with the California Institute of Technology, NASA supports research and systems engineering studies at JPL in the communications satellite area. Since BSS (Sound) represents a potentially beneficial use of space communications technology, NASA and JPL are performing system trade-off studies, propagation studies and technology development and demonstration efforts to explore a range of BSS (Sound) system concepts that might serve a variety of user needs.

The work in satellite sound broadcasting is built upon, and shares technology with, other past and present JPL communications satellite projects. Examples include the MSAT-X task, which involved digital mobile satellite technology development and satellite experiments, and the ongoing ACTS Mobile Terminal task, which extends mobile satellite technology development and testing to the 20/30 GHz bands.

This article describes the system trade-off study, propagation study, satellite experiment and demonstration effort, and receiver development currently underway at JPL under the Direct Broadcast Satellite–Radio (DBS–R) Program.

Background

Systems for the direct broadcast of sound by satellite have been studied for several years by various organizations. While both analog (FM) and digital systems have been proposed, the advantages of digital broadcasting are becoming more apparent as the necessary technology is developed. Digital sound technology is finding application not only in satellite systems, but in terrestrial communications and in audio recording/reproduction systems as well.

The key to digital DBS–R is efficient digital audio compression. If the bit rate required to faithfully reproduce sound is made low enough, digital systems can outperform analog systems in bandwidth utilization efficiency and satellite power requirements. In addition, the techniques that are available in the areas of coding and other types of signal processing can make digital systems more robust in difficult environments, such as those involved in mobile reception.

About a year ago, in light of the consideration of an allocation to BSS (Sound) at WARC-92, NASA determined that a need existed for study and technology development efforts designed to explore the possibilities of such a service. JPL, together with NASA's Lewis Research Center, was asked to put together a comprehensive three-year program to look at a range of systems issues involved in DBS–R. The resultant program, with supplemental support from the United States Information Agency (USIA)/Voice of America, contains seven tasks: 1) Systems Studies, 2) Propagation Studies, 3) Satellite Experiment and Demo, 4) Receiver Development, 5) Market Studies, 6) Regulatory and 7) WARC Preparation. Tasks 5 through 7 are being carried out by the Lewis Research Center. Tasks 1 through 4 are the responsibility of JPL. The goals of the four JPL tasks and the progress to date on each are described below.

Systems Studies

The goal of the systems studies task is to examine the elements of a DBS–R system over a sufficient range of parameters to allow a system provider the flexibility of defining a system suitable for a wide range of user needs and markets.

The DBS–R systems studied to date and documented by the CCIR have been very high data rate systems, on the order of 256 kbps, suitable for stereo CD quality music. Examples are the Eureka-147 system, developed by the European Broadcasting Union, and the system proposed by Satellite CD Radio in the United States.

We have decided to look at a wider range of data rates because there are likely to be applications that can be satisfied at lower rates, which would result in a substantially lower cost per program. These applications may include a range of program material from near-CD quality, through voice and music at a range of qualities from current FM to AM, through good voice quality news broadcasting, to emergency broadcasting.

Since the data rate directly drives satellite power and bandwidth requirements, a system provider may want to trade fewer high-quality channels for a larger number of low-rate channels.

The other factor that strongly drives a system design is the reception type, whether mobile or fixed, and the type of environment the receiver is expected to operate in. Again, since each environment requires a different link margin for reliable reception, a system provider may wish to simplify his system by limiting service to specific environments.

Reception Types and Associated Propagation Issues

The two main categories of reception are usually defined as mobile and fixed/portable. Each of these has some unique impairments to signal reception, the severity of these impairments being a function of the environment (e.g., rural, suburban or urban).

The mobile reception environment is dynamic, being characterized by periods of line-of-sight reception interrupted by signal blockage by roadside obstacles such as trees, telephone poles and buildings. These obstacles can cause signal attenuation on the order of

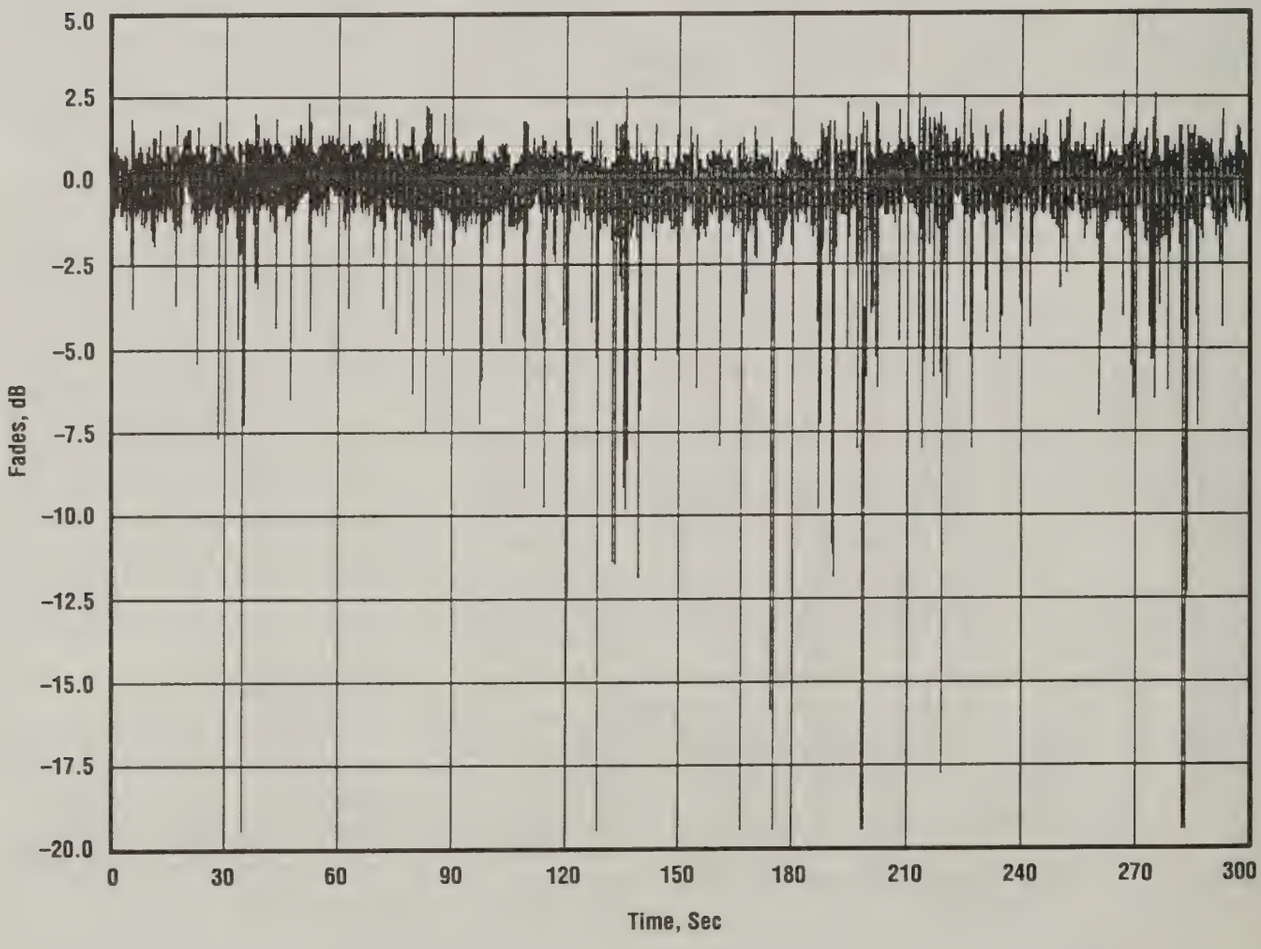

Figure 1. Satellite signal measurements under mobile conditions in rural environment.

15 to 20 dB, as shown in Figure 1. The signal blockage cannot be compensated for by providing sufficient link margin in a practical satellite-based system. One approach to blockage mitigation is the use of data interleaving and coding. For sufficiently short signal interruptions, the interleaving tends to spread error bursts out in time, allowing the decoder to correct them.

There is a practical limit to the amount of interleaving that can be implemented, and therefore there is a limit to how heavily shadowed an environment can be tolerated. It is generally accepted that providing mobile reception service to urban and heavily built up suburban areas will require hybrid satellite–terrestrial systems with urban boosters.

The environment for fixed and portable reception is more static, being characterized indoors by excess path loss, which is a function of the building type and the receiver's location within the building. Recent results from the propagation task, however, have shown that the indoor environment can be spatially and spectrally complex. Standing waves and frequency-dependent nulls can form due to reflections within a building. Since standing waves usually occur about half-a-wavelength apart, a mitigation technique currently under examination is the use of antenna diversity. Placing two or more antennas a few centimeters apart may ensure that at least one ends up in a strong signal zone. For other problems, such as excess path loss due to building walls, the only possible solution may be to move the receiver or a detachable antenna to a window with an unobstructed view of the satellite.

Providing a sufficiently robust system design is thus a compromise between providing a sufficient amount of link margin and the use of various link impairment mitigation techniques. By electing to provide service limited to certain user groups or environments, the system designer may make the system simpler and less costly.

For the purpose of further system tradeoff studies, we have tentatively selected link margin requirements on the order of 5 to 6 dB. Table 1 shows example link budgets for mobile and portable reception for a 48-kbps program at a 1-GHz transmission frequency. The main difference between the mobile and portable reception scenarios is in the required E_b/N_o. It is assumed that coherent demodulation can be used in the portable receiver while a less efficient differential demodulation scheme must be employed in the mobile receiver. However, if the building penetration loss for the portable reception system can be limited to a few dB, perhaps by positioning the receiver in a favorable location, the overall margin requirement for the two systems becomes similar.

Program Quality Versus Data Rate

In the digital reproduction of sound, the sampling rate is set by the Nyquist Criterion to be at least twice the bandwidth. Between 8 and 12 bits per sample are used, which results in a data rate on the order of 400 kbps for a 20-kHz audio bandwidth. Recent work in audio compression has reduced the data rate required to reproduce this bandwidth to around 128 kbps. While this is not an exact reproduction, the characteristics of the human auditory system make the reproduction subjectively indistinguishable from full data rate reproduction.

Reduction in data rate from this point can be achieved by restricting the audio bandwidth to be digitized and using more compression while accepting the resultant reduction in sound quality.

Data rates of 128 kbps, or 256 kbps for stereo, are thus the high end being considered for DBS–R. Somewhat lower data rates, from 64 kbps down to 16 kbps, may prove satisfactory for a range of entertainment and other applications. Much lower data rates can be considered for applications that only involve voice. For example, in the United States data rates as low as 2.4 kbps are used for digital voice applications. While not of very high quality, voice at 2.4 kbps could be used in such applications as emergency broadcasting.

The next step up in voice quality is at 4.8 kbps. Systems such as the Mobile Satellite Service and terrestrial digital mobile telephone are standardizing on voice at data rates of around 4.8 kbps.

The reproduction of music, even with restricted bandwidth, requires a higher data rate. Table 2 lists what is currently considered the range of data rates required to reproduce voice and music at various qualities.

Table 1. Example link budgets for monophonic digital sound at 48 kbps, rate 1/2 convolutional coding; all calculations normalized to a transmission frequency of 1 GHz

Parameter	Mobile reception		Portable reception	
	Mean	Tolerance (±)	Mean	Tolerance (±)
Information bit rate program, kbps	48.00		48.00	
Transmitter power per program, W	3.00		3.00	
Transmission frequency, GHz	1.00		1.00	
Satellite antenna diameter, M	7.00		7.00	
Satellite antenna gain, dB	34.70		34.70	
Satellite antenna beamwidth, deg	3.00		3.00	
EIRP per program, dBW	39.48		39.48	
Receiver antenna gain, dB	4.50	0.50	5.00	0.50
Received signal power, dBW	–140.50	0.50	–140.00	0.50
Receiver system temperature, dBK	24.00	1.00	24.00	1.00
Receiver system G/T, dB/K	–19.50	1.12	–19.00	1.12
E_b/N_o available at beam edge, dB	14.29	1.12	14.80	1.12
Required E_b/N_o for BER = 1.0E-5, dB	7.00	1.00	4.50	0.50
Building penetration loss,* dB	N/A	N/A	3.00	3.00
Implementation loss, dB	1.50	0.50	2.00	0.50
Link margin at beam edge, dB	5.79	1.58	5.80	3.30

* *Favorable location within building.*

Table 2. Required data rates versus quality of compressed audio

Data rate, kbps	Compression algorithm	Potential applications	Potential quality
2.4	LPC-10	Emergency broadcast	Less than telephone
4.8	CELP	News (voice)	Telephone
16–20	Adaptive LPC/subband	Voice and music	Terrestrial AM mono
48–64	Transform/subband	Voice and music	Terrestrial FM mono
192–256	Transform/subband	Voice and music	CD stereo

Satellite Configuration Analysis

Once the data rate for the required audio quality is selected and the link margin requirement is determined, estimates can be made of the required satellite power, size and cost as a function of the number of programs and the desired coverage area.

When planning a system that is to cover a large country or region, individual satellite beams are placed so as to fill in the contours of the area to be covered. Circular beams are the most straightforward to generate. For better coverage of the intended area, some beam shaping is possible, but usually with a penalty of having to use a larger satellite antenna.

The range of beam size considered practical at L-band is from about 1 to 3 deg in diameter. Figure 2 shows examples of 1- and 3-deg beam coverage of two countries in South America from a satellite in geostationary orbit at 70° W longitude. The figure also shows the satellite's 30-deg elevation contour.

Figure 3 shows a curve of required RF power per program, from a geostationary satellite with a 3-deg antenna beamwidth, as a function of the transmit frequency. The link parameters are taken from Table 1. This power curve scales as beam diameter squared.

Figure 2. 1- and 3-deg beam coverage.

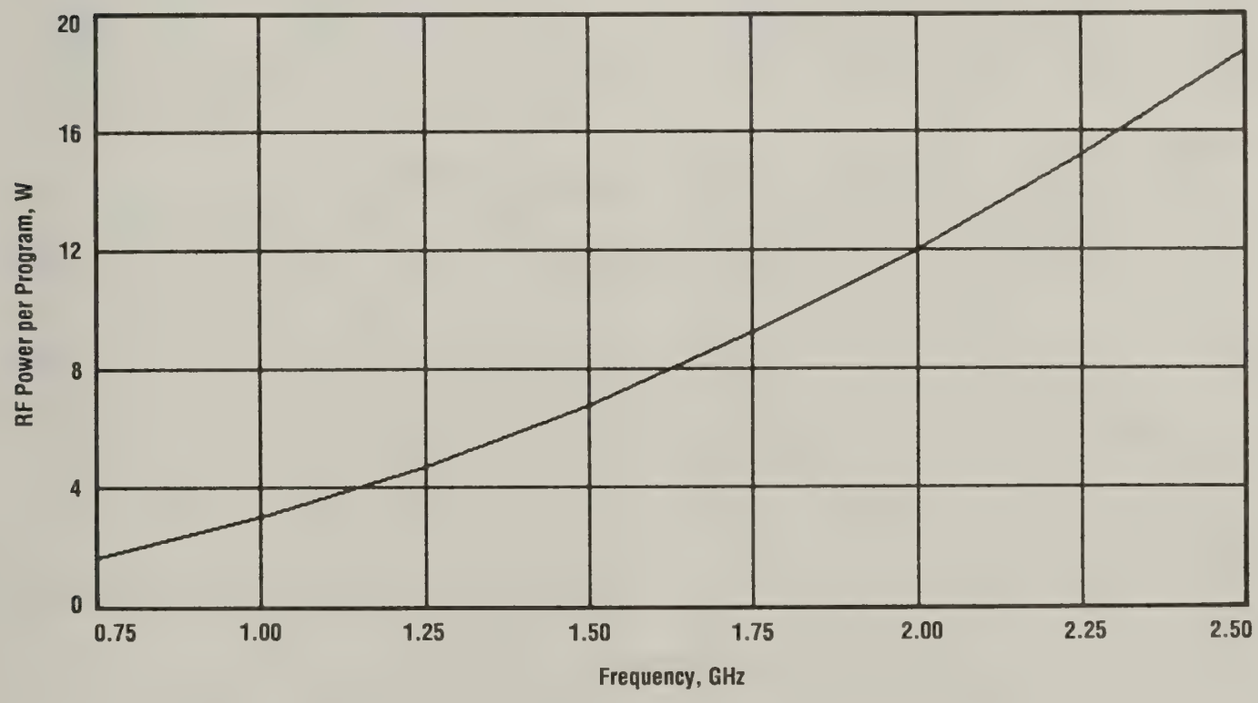

Figure 3. Required RF power per program with 3-deg antenna beamwidth.

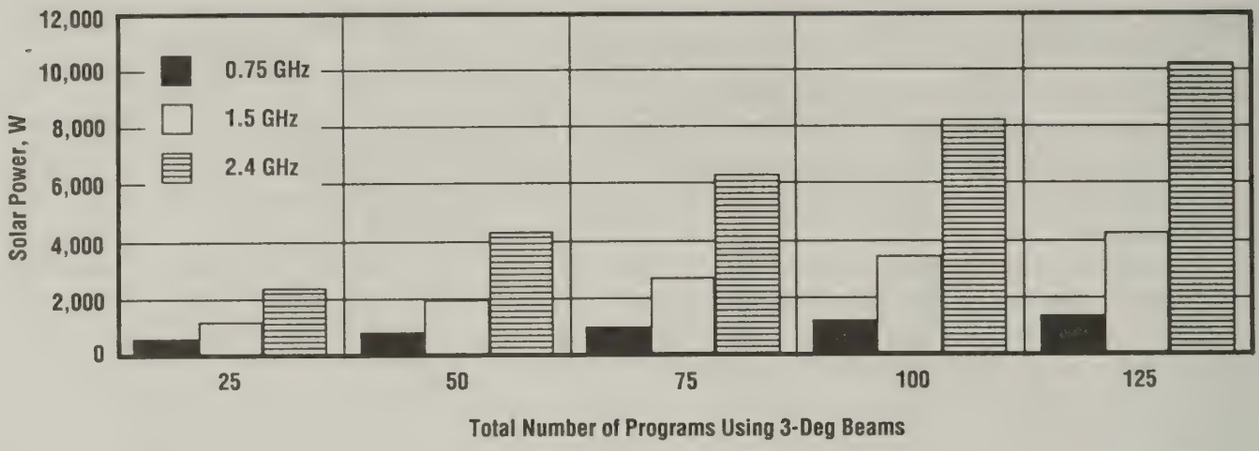

Figure 4. Satellite solar power requirements.

Figure 4 shows the solar power requirements for a satellite transmitting 25 to 125 programs, each at 48 kbps, also assuming 3-deg beams.

There is no advantage to using several smaller beams over one larger beam to cover a given area, except when program separation is required between regions in the coverage area. Smaller beams require larger satellite antennas, which results in higher satellite costs. As part of the systems study, we are generating satellite weight and cost models whose main inputs are transmit power requirements and antenna size and complexity.

Propagation Studies

The propagation studies task is being performed under the auspices of the NASA Propagation Program. This Program has been going on for a number of years and has produced a great deal of propagation measurement data at frequencies of around 850 MHz (UHF) and 1550 MHz (L-band). While these frequencies were studied because of the then ongoing MSAT-X program, much of the data are applicable to DBS–R.

Mobile Environment

Most of the propagation measurements accomplished prior to 1990 under this Program were aimed at defining propagation effects in the mobile environment. First balloons, then helicopters, were used to transmit signals that were received by a mobile test van. Finally, in 1989, when the Japanese experimental satellite ETS-V became available, the test van was sent to Australia to take a series of measurements of the much stronger L-band signal available from this satellite. The test van employed both directional and non-directional antennas for receiving the satellite signal.

Satellite signal strength measurements in Australia were made over a range of reception area types, from very lightly shadowed rural areas to more heavily shadowed suburban and urban areas. Figure 1 is an example of one of the measurements made in a rural area.

Indoor Environment

Most propagation measurements for indoor reception to date, for example the tests with the U.S. experimental satellite ATS 6 at UHF and L-band, emphasized the measurement of the average attenuation to be expected from buildings of different construction. There were also indications of signal strength variations within buildings caused by internal reflections and other phenomena, but these were not well quantified. For this reason, the emphasis of Task 2 of this study was on obtaining more data on the fine structure of propagation phenomena within buildings.

The propagation measurements are being accomplished under contract with the University of Texas at Austin. The test configuration is illustrated in Figure 5. The test equipment is

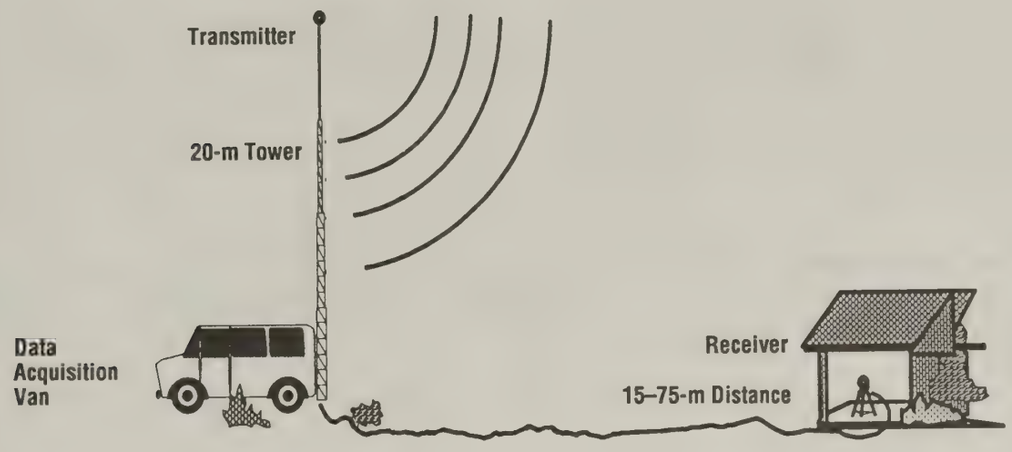

Figure 5. Indoor propagation measurement test configuration.

capable of sweeping a signal over a range of 700 to 1800 MHz and making spot checks at other frequencies. The receiving antenna can be moved to various locations inside a building. It is expected that the results of these measurements will provide a significant contribution to the understanding of DBS–R fixed and portable reception in an indoor environment.

Propagation Modelling

In testing a system it is important to reproduce the link conditions as faithfully as possible. For hardware testing at JPL, we have a channel simulator that can produce link impairments such as additive white Gaussian noise (AWGN) and multipath-induced fading. We have recently added the capability of driving the channel simulator with measured propagation data, such as the test data obtained in Australia.

Since there are so many possible paths for a mobile receiver to take, it is important to standardize on some repeatable test conditions. One option is to use a specific set of propagation measurements covering a range of environments. Another is to use a statistical model, such as a two-state, or higher, Markov model, to reproduce the blockage effects of a mobile link. This type of model is particularly useful in software simulations. We have started to develop these models and have used them to investigate the effects of varying such system parameters as interleaver length.

Satellite Experiment and Demonstration

The goal of the satellite experiment and demonstration is the field testing of end-to-end DBS–R transmission and reception in a range of environments, utilizing an existing L-band satellite. JPL intends to accomplish these tests prior to the end of 1991 in order to provide both field test results and listener exposure to DBS–R sound via satellite prior to the 1992 WARC.

The demonstration system is being assembled from a combination of commercially available hardware and existing experimental equipment from the JPL MSAT-X Program. This combination of equipment is expected to provide a fully adequate test system, with components of proven reliability, and yet permit field testing and demonstration of the DBS–R concept within the relatively short time remaining before the 1992 WARC.

Satellite

There are very few satellites available that operate in the L-band and are suitable for a DBS–R test. Two possibilities are both INMARSAT satellites, MARECS-B2 and MARISAT. Because of limited available power, the maximum data rate that can be supported by these satellites is on the order of 19 kbps. Even this low rate requires that the MSAT-X medium-gain antenna be used for signal reception.

Table 3 shows the parameters for links with both satellites. The equipment is being designed with a fall-back data rate of 16 kbps in case the additional link margin of approximately 1 dB is required. Since MARECS-B2 has more power than MARISAT, it is the more suitable satellite for this test. A request for test time on MARECS-B2 was submitted to INMARSAT. If this time is granted, the satellite tests will be performed around September 1991, and a public demonstration will be conducted in October. Figure 6 shows a set of constant

Table 3. Link parameters for satellite experiment

Parameter	MARECS-B2	MARECS-B2/MARISAT	MARISAT
Satellite EIRP, dBW	36.00		28.50
Percentage used	18.40		99.44
EIRP used	28.65		28.48
	Data	**Pilot**	**Data**
Transmitter			
EIRP, dBW	27.19	23.19	26.95
Path			
Space loss, dB	–187.75	–187.75	–187.75
Frequency = 1.54 GHz,			
range = 38,000 km			
Receiver			
Antenna gain, dB	10.00	10.00	10.00
Pointing loss, dB	–1.00	–1.00	–1.00
System temperature, dBK	24.18	24.18	24.18
N_o, dBW/Hz	–204.42	–204.42	–204.42
Performance			
Received signal power, dBW	–151.56	–155.56	–151.80
Received C/N_o, dB	52.87	48.87	52.63
Data rate, kbps	19.20		19.20
Link E_b/N_o, dB	10.03		9.79
E_b/N_o required, dB	6.00		6.00
Implementation loss, dB	–1.00		–1.00
Available margin, dB	3.03		2.79

elevation contours for MARECS-B2, which is located at 55.5° W longitude. The tests and demonstration will be performed on the East Coast of the United States.

Equipment Development

The commercial equipment to be used consists of a vocoder that encodes an audio bandwidth of 3 kHz and is capable of operating at both 16 kbps and 19.2 kbps.

MSAT-X equipment consists of the mechanically steered tracking antenna, an L-band receiver and a test van that includes instrumentation for recording received signal strength and other test points. The van also has a video recording camera on its roof. The camera will be pointed in the direction of the satellite to visually record line-of-sight conditions.

A modem has been completed. Its design is based on MSAT-X experience and includes such design features as differential demodulation, Viterbi decoding, a variable length interleaver and the ability to maintain bit timing integrity through long periods of signal blockage.

Figure 6. Constant elevation contours for MARECS-B2 at 55.5° W longitude (20-, 30- and 40-deg elevation angles).

Laboratory Tests

Prior to the field tests, the equipment will undergo a comprehensive set of tests in the laboratory using the channel simulator. The test configuration is illustrated in Figure 7.

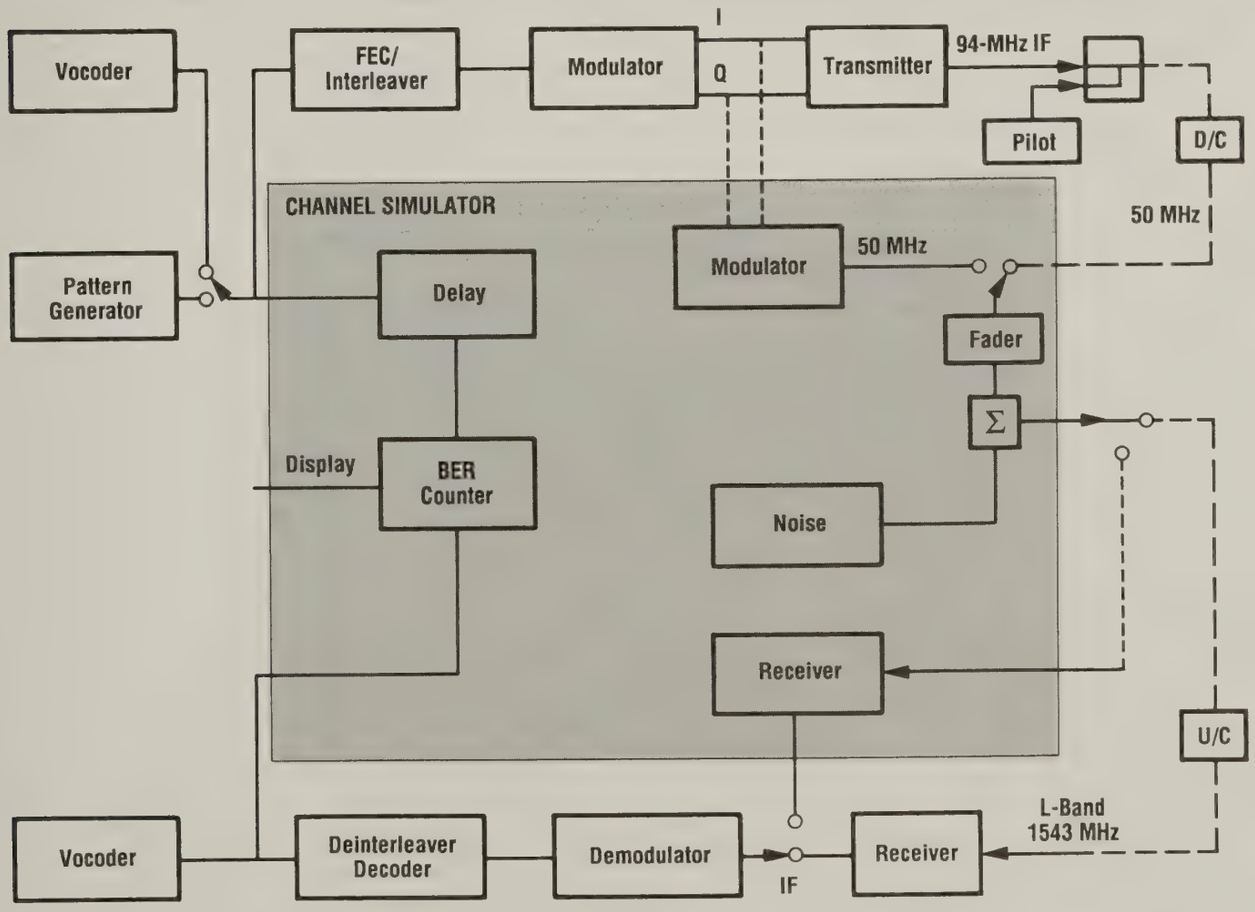

Figure 7. Laboratory test configuration for experimental DBS–R system.

Field Tests

Field tests will be performed on the East Coast of the United States, most likely in the vicinity of the COMSAT Coast Earth Station at Southbury, Connecticut.

The main objective of the field tests is to obtain quantitative and qualitative assessments of system operation under mobile reception conditions in several types of terrain. The key system parameter that will be varied is the interleaver length, at 0.0, 0.5 and 1.0 second.

Demonstration

The public demonstration of the system is tentatively set for October 1991 in the Washington, D.C., area.

Receiver Development

The fourth task of the JPL effort is the receiver development task. This task started in January 1991, with the first phase being the definition of the functional requirements.

The objective of this task is to develop a versatile receiver design and functional breadboard that will incorporate all the important features that need to be tested and investigated further. These include such capabilities as the accommodation of a wide range of data rates, antenna diversity and the capability of operating in a hybrid satellite–terrestrial broadcasting system.

Conclusion

The goal of the DBS–R Program is to explore some of the range of user needs that can be satisfied by such a service. Currently, within the United States, at least three commercial organizations have applied to provide direct radio broadcast by satellite, with specific user needs in mind. It is hoped that the DBS–R Program, together with industry, will explore a variety of DBS–R system configurations that may satisfy a range of sound broadcasting user requirements around the world. It is also hoped that the technical knowledge gained from these efforts will provide a valuable source of information to aid decision-making at the 1992 WARC.

The contributions made to JPL's study by the USIA/Voice of America, the University of Texas and the Lewis Research Center and its contractors are gratefully acknowledged.

Cost Study for MSAT-X Ground System

Byron Jackson, Systems Engineer
Jet Propulsion Laboratory

The MSAT-X Program at JPL has developed a prototype ground unit for a mobile satellite system (MSS). This ground unit includes a transmitter/receiver, modulator/demodulator, voice coder, terminal processor and several antenna designs for test and evaluation. Extensive field testing has established the technical feasibility of the ground unit. This article reports on a study of the economic feasibility of the ground unit.

Methodology of the Cost Study

The cost study used a "bottoms up" methodology — a detailed cost engineering approach made possible by having complete designs for the key elements of the ground unit. The designs for each key element were carefully reviewed with the engineers to see how the designs could be modified so as to best represent a commercially produced unit. In addition, designs were developed for an operator communication device and a trunk-mounted chassis, including a power supply and a heat sink. The complete ground system, consisting of an antenna system, voice coding and signal processing unit and operator's communication device, is shown in Figure 1. Quotes were obtained for the cost of parts and estimates were developed for the equipment and labor hours required to assemble the ground unit. This information was converted to complete manufacturing cost (selling price) estimates using the SAMICS costing program, a detailed cost engineering model developed at JPL.

The time frame for the cost study was the early 1990s, corresponding to the expected launch of the first MSS satellite. Production cost estimates were confined to the needs of this initial venture; the output was limited to 1,000, 5,000 and 10,000 units per year, although higher production levels could lead to significant cost reductions.

A steerable roof-mounted antenna — one that was reasonable in appearance (low profile) and could function effectively while the vehicle was in operation — provided the greatest technical challenge for the MSAT-X Program's ground-system research and development effort. Four separate antenna concepts were developed and tested with reasonable success. Because each antenna concept has its own advantages, cost estimates are reported here for all four.

Results of the Cost Study

The results of the cost study are summarized in Table 1. Given the modest production levels from a commercial perspective, the results are promising. Based on cost, the microstrip Yagi-Uda array antenna was the most attractive. At 10,000 units a year, the estimated manufacturer's selling price of the ground unit with this antenna was $4,175. At lower production volumes, the ground-unit cost increased — to $4,292 at 5,000 units a year and $5,689 at 1,000 units a year, an increase of 3% and 36%, respectively.

The electronically steered phased array antenna provided the lowest roof profile but was the highest in cost. At a production volume

Table 1. Estimated manufacturer's selling price for MSS ground unit components, dollars

Component	Annual production		
	1,000 units	5,000 units	10,000 units
Antennas			
Microstrip Yagi-Uda array	1,046	657	634
Mechanically steered linear array	1,434	1,126	991
Mechanically steered planar array	1,833	1,569	1,475
Electronically steered phased array	2,762	2,262	2,026
Voice coder	273	258	246
Modulator/demodulator	514	415	399
Terminal processor	27	23	23
Transmitter/receiver	2,665	2,126	2,081
Chassis and power supplies	703	527	517
Operator communication device	461	286	275
Totals with indicated antenna			
Microstrip Yagi-Uda array	5,689	4,292	4,175
Mechanically steered linear array	6,077	4,761	4,532
Mechanically steered planar array	6,476	5,204	5,016
Electronically steered phased array	7,405	5,897	5,567

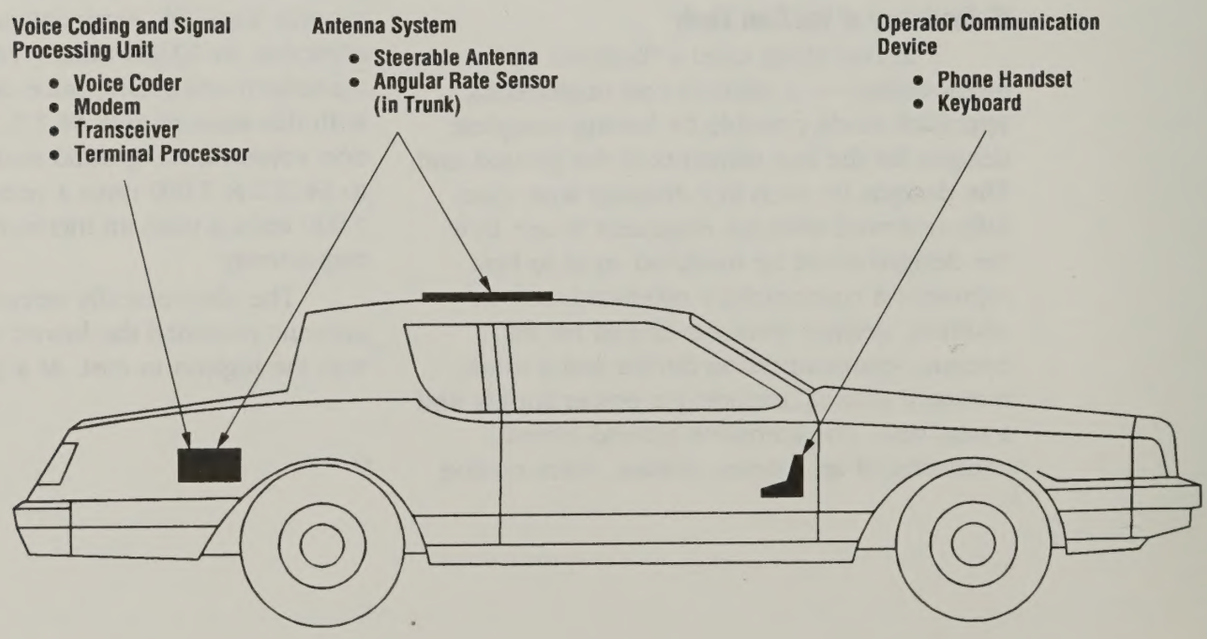

Figure 1. Complete ground system for mobile satellite communications.

of 10,000 units a year, the estimated manufacturer's selling price of the ground unit with this antenna was $5,567, a 25% increase over the cost of the ground unit with the Yagi-Uda antenna; the antenna cost rose from $634 to $2,026 each.

The transmitter/receiver was the largest element of cost, accounting for 50% of the total cost of the ground unit with the Yagi-Uda antenna and at an annual production level of 10,000 units. For the same ground unit–antenna configuration and production level, the combined cost of the voice coder and modulator/demodulator accounted for 15% of the total cost. The transceiver and modem/vocoder could provide significant cost reductions at higher production levels. On the other hand, the antennas are relatively unique and complicated in construction. Further technology innovation may prove to be the most effective way of reducing the antenna's share of the total cost.

Conclusion

Based on the study performed, the MSAT-X Program was successful in developing a prototype MSS ground unit that is promising in cost at the modest production levels that can be expected of industry during the first years of development.

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Satellite Sound Broadcasting	Arvydas Vaisnys	161-228	354-6219
Orbital Env. Handbook	Andrew Beck	301-466	354-4575
MSAT-X	Richard Emerson	238-420	354-3848
ACTS Mobile Terminal	Thomas Jedrey	238-420	354-5187
Technology Transfer	Valerie Gray	601-237	354-1260

**Area code 818. The prefix number for FTS users is 792.*

Upcoming Events

The International Conference on Communications (ICC) will be held in Denver, Colorado, June 23–26, 1991. JPL is organizing two of the many sessions.

Session 35A, "The Role of Satellites in a National Telecommunications System at the Turn of the Century," will be organized and chaired by Polly Estabrook of JPL. Three papers will be given at the session.

Session 43, "Recent Advances in Data Communications," will be organized by Dariush Divsalar of JPL and chaired by N. Seshadri of AT&T Bell Laboratories. Six papers will be given at the session.

For more information about the conference, contact Russell S. Johnson, ICC '91 General Chairman, at (303) 721-5650.

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